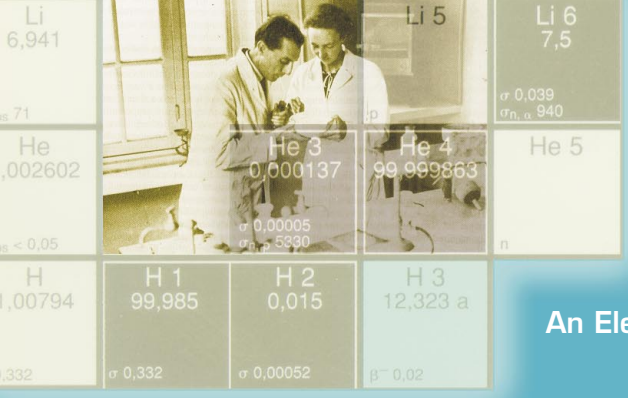

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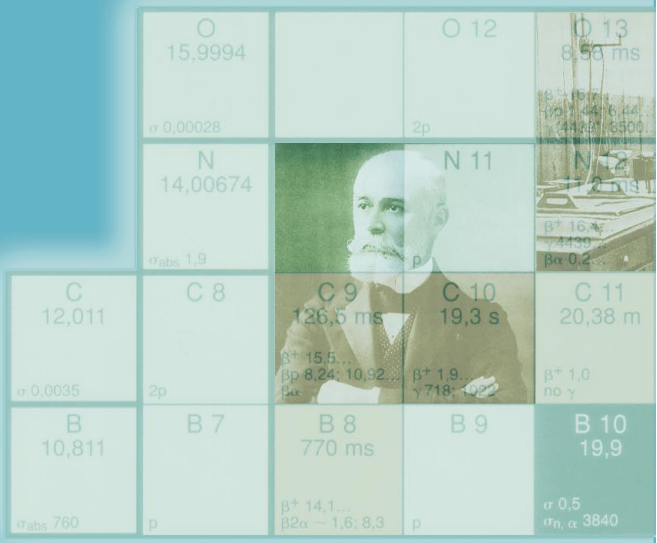

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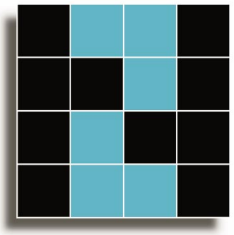

Nuclides 2000

An Electronic Chart of the Nuclides

User's Guide

Joseph Magill • 1999

EUR 18737 EN

Institute for Transuranium Elements

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NUCLIDES 2000
An Electronic Chart of the Nuclides

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Contents

1. Introduction

1.1. General

Radionuclides have many applications in agriculture, medicine, industry and research. For people working with such materials, the 'Chart of the Nuclides' is an indispensable tool for obtaining basic data and investigating radioactive decay schemes. Since the publication of the original Karlsruhe chart, many others have appeared. In all cases, however, one has to process the basic data contained in these charts to obtain the required information (e.g. to obtain nuclide masses, activities, radiation dose rates, radiotoxicities etc. resulting from radioactive decay of a parent nuclide).

This was the primary motivation for the development of *Nuclides 2000* software package on CD-ROM. In addition to providing the basic data on radionuclides, it allows full time-evolution of the parent and daughter nuclides through an exact solution of the equations governing radioactive decay. From the amounts of the nuclides present at any time, quantities such as activities, gamma dose rates, radiotoxicities, etc. are evaluated.

The database included in this package is based on the Joint Evaluated File Library, JEF 2.2.

1.2. System Requirements

To run this version of *Nuclides 2000*, the following are the minimum system requirements:

- IBM or compatible PC with a 486/66 MHz processor (Pentium II, 350 MHz recommended).
- 2× CD-ROM drive.
- Mouse or other pointing device.
- 16 MB RAM, 75 MB free hard disk space.
- SVGA monitor 15″ (17″ or 19″ recommended), 800×600 resolution, 256-colour video display (16 bit colour recommended).
- Microsoft Windows 95, 98, or NT 4.0 operating system. With Windows NT (service pack 4 is recommended), the application should be installed by the administrator.
- to view articles and the online users guide the HTML Help Viewer is required. The Help Viewer requires that Microsoft Internet Explorer (version 4.00 or later) be set up on the user's computer. It is not required, however, that the Internet Explorer be used as the system's default browser.
- Web browser for the Online Features. Modem, 9600 baud or faster.

As with many applications, the higher the system resources, the better this application will run. The software is available for standalone PCs.

1.3. Installation

The *Nuclides 2000* CD comes with an installation program which

- creates a directory on your hard disk
- copies all required files into that directory
- copies the *original* database from the CD to a *personal* database on the hard disk which can be edited and extended
- creates a *Nuclides 2000* program group in Windows.

To install the application:

1. Place the *Nuclides 2000* CD into the compact disk drive.
2. Run the *setup.exe* program.
3. Follow the instructions on the screen.

The program can be un-installed from the *Nuclides 2000* program group through: S*tart/Programs/Nuclides 2000/Uninstall.*

During the installation procedure, a *Nuclides 2000* program group is added to the *Start, Programs* menu. This program group consists of five items: *Articles*, *Nuclides 2000*, *Nuclides 2000 Help*, a *Read Me* text file, and *Uninstallation*. Latest information is contained in the *Read Me* text file. The main application can be launched by clicking on the *Nuclides 2000* item. From within this application, the *Articles* and *Nuclides 2000 Help* can also be accessed. An electronic version of the User Guide–*Nuclides 2000 Help*–can also be accessed from the program group. The *Articles* item in the program group leads to a sub-group containing *Articles* and *HTML Help Update.* The articles can be accessed by clicking on *Articles.* If this

does not work, it means that the HTML Help (used to view the articles) has not been installed on the user's machine. If this is the case, the user should first install the HTML Help by clicking on the *HTML Help Update* item.

1.4. Scientific Notation

In scientific notation, a number is given as a mantissa multiplied by a power of ten. The letter E separates the power of ten from the mantissa i.e. 1.23456E-13. In this example, the mantissa is 1.23456. It is separated by the letter E from the exponent -13. Written explicitly, the above number becomes 1.23456×10^{-13}. For calculations, a number can be input as a mantissa and an exponent e.g. a mass of 1 gram can be input as 0.1E1, 1E0 or 1.

Ranges of Numbers

The range that real numbers x can take in computations is:

4.94065645841247E-324<abs(x)<1.79769313486232E308

where abs(x) is the absolute value of x. Numbers outside this range will lead to overflow and underflow errors.

2. The Opening Screen

As soon as the application has been installed, it can be started by double clicking on the *Nuclides 2000* program icon. After a few seconds the opening screen appears as shown in *fig. 1.*

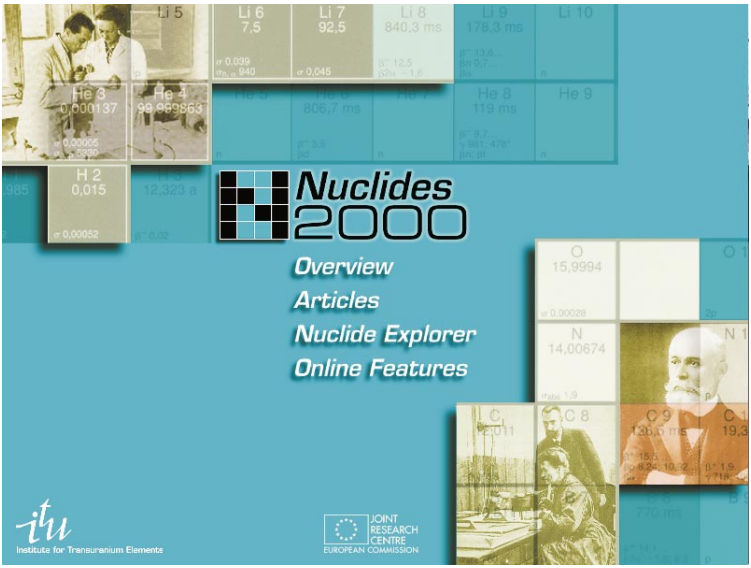


Fig. 1. *The opening screen in Nuclides 2000.*

In the background a section of the Karlsruhe Chart of the Nuclides is shown. Superimposed on the nuclides chart are photographs of some of the pioneers of radioactivity e.g. Becquerel, the Curies (bottom right), and Curie and Joliot (top left). From this opening screen, there are four options available to the user:

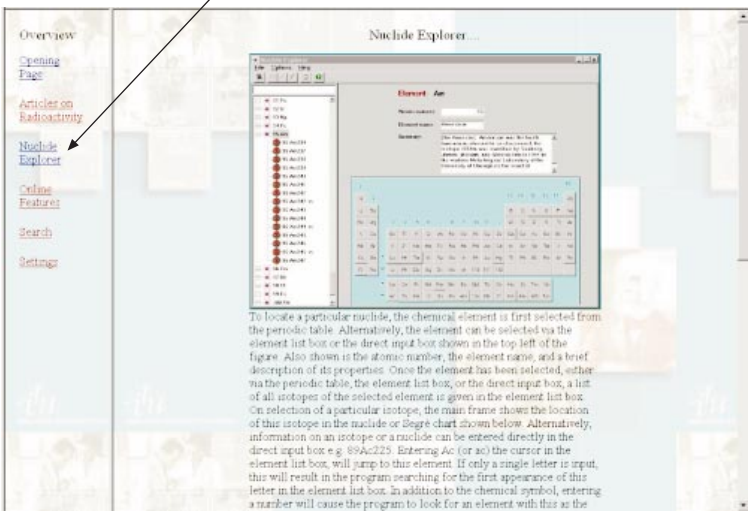
- Overview
- Articles
- Nuclide Explorer
- Online Features.

Selection of any of these takes will open the corresponding window.

3. Overview

A summary of the various features of *Nuclides 2000* is contained in the Overview. This can be accessed directly from the opening screen shown in *fig. 1*. In this window the main features are briefly summarised, i.e.

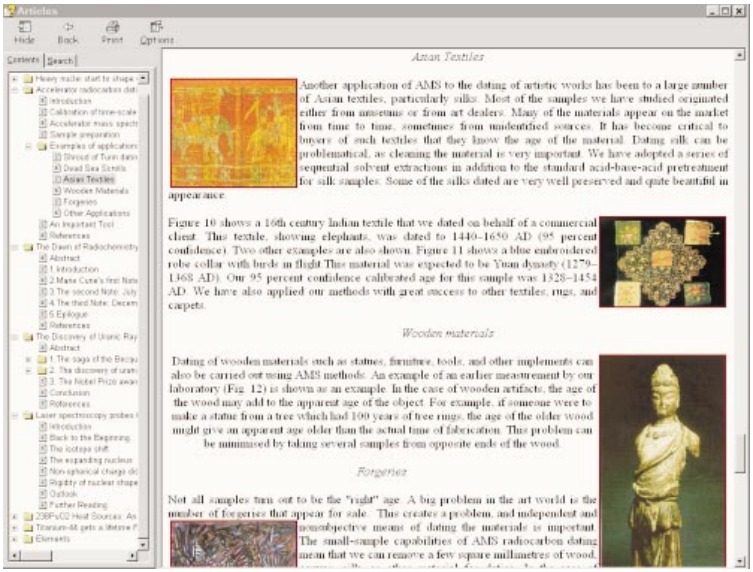
- Opening Page
- Articles on Radioactivity
- Nuclide Explorer
- Online Features
- Search
- Settings



The selection shown corresponds to the Nuclide Explorer. The nuclide explorer is used to navigate through the periodic table of elements and through the nuclide chart. The Nuclide Explorer is the "engine" behind the entire program in that it allows one to access the nuclide decay data and perform extensive decay calculations.

4. Articles

In the Articles window, which is also accessed from the opening screen shown in *fig.1*, a selection of articles on various aspects of radionuclides, ranging from radiocarbon dating to the formation of ^{44}Ti (an isotope of titanium) in supernova. There are also articles covering the history of radioactivity and radiochemistry and descriptions of all the chemical elements. The selection shown below is from an article on *Accelerator Radiocarbon Dating of Art, Textiles and Artefacts.*



This database of articles is fully indexed and can be searched for keywords. Use of wildcards and jokers is allowed in the keyword selection, e.g. radioactivity, rad*, ???om*, etc. The displayed topic contains the keyword

highlighted wherever it appears in the text. As an example, one could find the price of various elements by entering the "$" symbol as keyword. Another example, to find articles which contain an image of an element, would be to use the keyword "courtesy".

5. Nuclide Explorer

5.1. Navigational Interface

There are 112 known chemical elements and recently evidence for the existence of elements 114, 116 and 118 have been reported. Each element is characterised by atoms containing a fixed number of protons, denoted by the atomic number Z, in the nucleus and an equal number of orbital electrons to ensure electrical neutrality. In addition to protons, the nucleus contains a variable number N of electrical neutral neutrons. Atoms of an element with different numbers of neutrons but fixed number of protons are known as isotopes of that element. Elements can have many isotopes, but most of these are unstable. In general, an atom with atomic number Z, and neutron number N is known as a nuclide. More than 2700 nuclides are known, but only about 10 % of these are stable. The total number of protons plus neutrons is known as the mass number A of a nuclide. A nuclide can be specified by the notation:

$${}^{A}_{Z}X_{N}$$

Z is the atomic (proton) number
N is the neutron number
A is the mass number (N+Z)
X is the chemical element symbol

Because of the relationships between Z, A, N (A=Z+N) and X, a nuclide can be uniquely specified by fewer parameters. A particular chemical element is uniquely specified by its symbol X or the proton number Z. A nuclide is uniquely specified by the element name X (or proton number Z) to-

gether with the neutron number N. Examples of such nuclides are ^{60}Co, Co^{60}, Co^{60}, Co-60, Co 60.

Because of the large number of nuclides, navigation through a chart of the nuclides is more complicated that navigation through the periodic table of the elements. However, in the first step, a periodic table of the elements is very useful for selecting the chemical element. For this reason, the starting window shown in the Nuclide Explorer contains a periodic table as shown in *fig. 5.1.1.* To locate a particular nuclide, the chemical element is first selected from this periodic table. Alternatively, the element can be selected via the *element list box* or the *direct input box* shown in the top left of *fig. 5.1.1.* Also

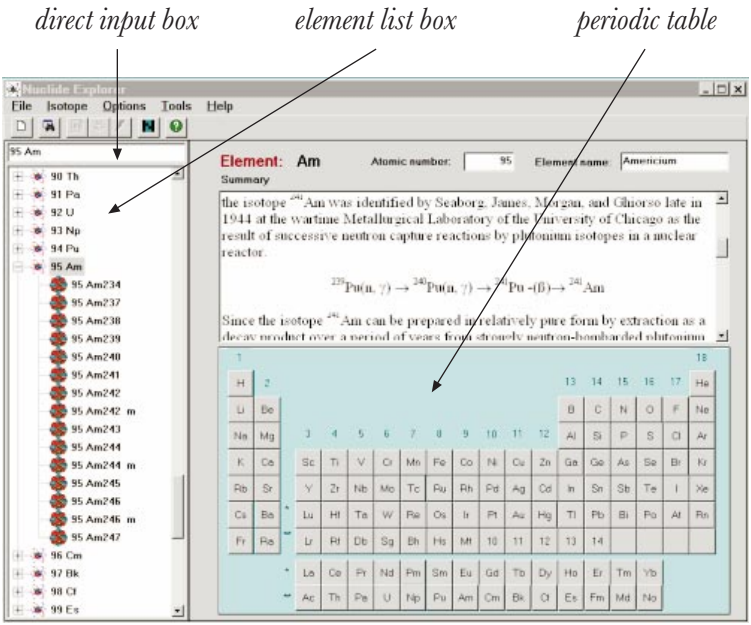


Fig. 5.1.1. *The navigational interface for element selection showing the periodic table, the element list box and the direct input box.*

shown in the main panel in *fig. 5.1.1* is the atomic number, the element name, and a brief description of its properties.

Once the element has been selected, either via the periodic table, the *element list box*, or the *direct input box*, a list of all isotopes is given in the *element list box*. On selection of a particular isotope, the main frame shows the location of this isotope in the nuclide or Segrè chart as shown in *fig. 5.1.2*.

Alternatively, information on an isotope or a nuclide can be entered in the *direct input box* in *fig. 5.1.1*. A nuclide can be entered directly in the form 89Ac225. Alternatively, entering Ac (or ac), the cursor in the *element list box* will jump to this element. If only a single letter is input, this will result in the program searching for the first appearance of this letter in

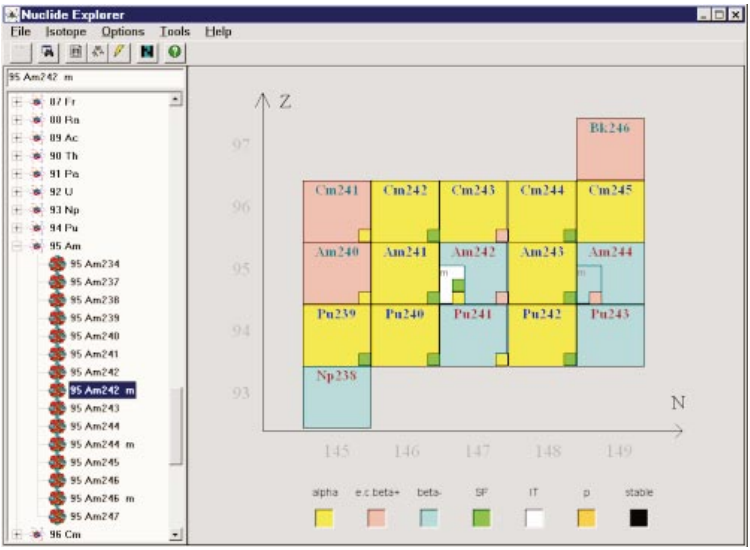


Fig. 5.1.2. *The navigational interface showing the location of the selected nuclide in the Segrè chart.*

the *element list box*. In addition to the chemical symbol, entering a number will cause the program to look for an element with this as the atomic number. Double clicking on this element will reveal all the isotopes of this particular element. Clicking again on a particular isotope will reveal the section of the nuclide chart containing this nuclide in the centre. Also shown in *fig. 5.1.1* is a brief description of the properties of the selected chemical element.

The nuclide or Segrè chart is essentially a plot of the number of protons, Z, vs. number of neutrons, N, in the nucleus. This particular way of arranging nuclide was first proposed by Segrè. As will be seen, this plot is particularly useful in revealing nuclear reaction processes and in particular nuclear decay. The nuclide selected in *fig. 5.1.2* is Am242m which has 95 protons (Z) and 147 neutrons (N) in the nucleus. The m refers to a long-lived metastable state of Am242. The mass number of this nuclide is then A=Z+N=242 and this value is also shown.

The first remark to be made regarding this Segrè chart is in connection with the use of colours. These colours refer to the fact that the nuclide is unstable (radioactive) and decays by a particular process or processes. The decay processes and their associated colours are shown at the bottom of the main frame in *fig. 5.1.2*. In the present version of *Nuclides 2000*, the user can select the colour schemes used in the original Karlsruhe, Strasbourg, and General Electric charts. In addition, a "personal" colour scheme can be created and used. In this section, the colours used correspond to the Karlsruhe Nuclide Chart.

In the example chosen, it can be seen that the nuclide Am242

decays primarily by ß- (blue) emission and to a lesser extent by ε/ß+ (red) emission. This is shown in more detail in *fig. 5.1.3*. The different types of radioactive decay are described in detail in Appendix 2. Also shown is the fact that Am242 has a metastable state denoted by m. The colour used in the metastable inset box indicates that Am242m decays primarily by IT (Isomeric Transition, white) and to a lesser extent by SF (spontaneous fission, green) and α decay (yellow).

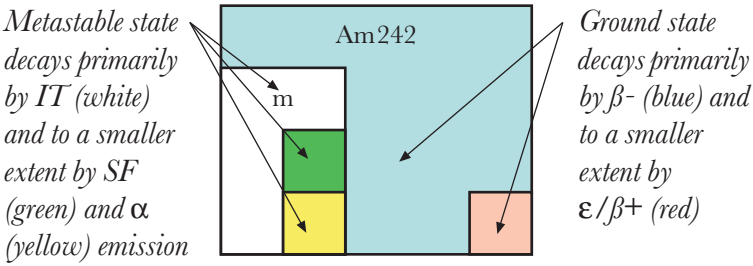


Fig. 5.1.3. *Description of the colours and symbols used in the Segrè chart.*

Decay Processes and Nuclear Reactions

As was mentioned earlier, the Segrè chart is particularly useful for understanding nuclear decay processes and nuclear reactions. The decay processes lead to a change of position of the nuclide in the Segrè chart as shown in *fig. 5.1.4*. A nuclide located in the centre (dark grey) will, following α, ß-, ε/ß+, n, or p decay processes, form a daughter nuclide at the positions shown by the various arrows. Hence, one can follow a decay path, for example, by selecting (clicking with the mouse) the daughter of the nuclide shown in the centre. The daughter nuclide then moves to the centre position in the Z, N diagram in *fig. 5.1.4*. This process can be repeated

until a stable nuclide is found. In addition, daughters of the Z, N nuclide can be highlighted through the use of the right mouse button.

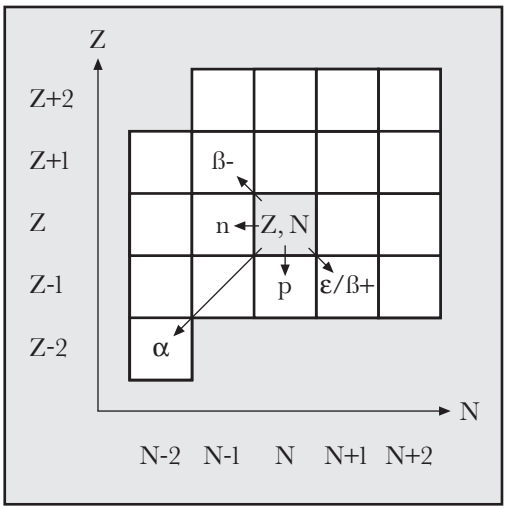


Fig. 5.1.4. *Radioactive decay processes on the Segrè chart. A nuclide with co-ordinates Z, N "decays" to the position shown depending on the process.*

The Segrè diagram is also very useful for investigation activation and nuclear reactions as shown in *fig. 5.1.5.* A target nuclide of element X (with Z protons and N neutrons, A=Z+N) will transform by reaction with particle a to nuclide Y (Z´ protons and N´ neutrons, A´=Z´+N´) with the emission of particle *b*. This reaction can be written:

$$^{A}X+a \rightarrow {}^{A'}Y+b$$

This reaction can be written more compactly in the form

$$^{A}X\,(a, b)\,{}^{A'}Y$$

The result of interaction of a variety of particles *a* (neutrons n, alpha particles α, deuterons d, gamma radiation γ, and protons p) with a target nuclide with co-ordinates Z, N is shown in *fig. 5.1.5* (adapted from the Karlsruhe Nuclide Chart). Although the present version of *Nuclides 2000* does not treat nuclear reactions and activation processes quantitatively, the reactions can be followed qualitatively with the help of *fig. 5.1.5* and the Segrè chart in *fig. 5.1.2*.

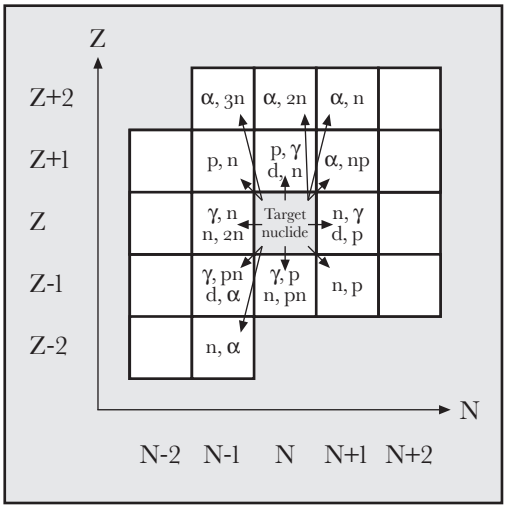


Fig. 5.1.5. *Activation processes and nuclear reactions on the Segrè chart. A target nuclide with co-ordinates* Z,N *transforms to the nuclide* Z´,N´ *through the processes shown.*

5.2. Data Sheets

Once the navigational task is finished, i.e. the nuclide has been selected, we can look at the Data Sheets. The data on each nuclide is based on the JEF 2.2 decay datafile. The information for each nuclide is presented in Data Sheets as

shown in the diagram. In each Data Sheet, the information given consists of *Decay Data*, *Mean Decay Energies*, *Discrete Energies*, *Radiotoxicity Data* and *Derived Quantities*.

5.2.1. Decay Data

At the top of the data sheet in *fig. 5.2.1*, general information consisting of the selected nuclide, its atomic weight and half-life are given. The notation used for the nuclide was described in the previous section.

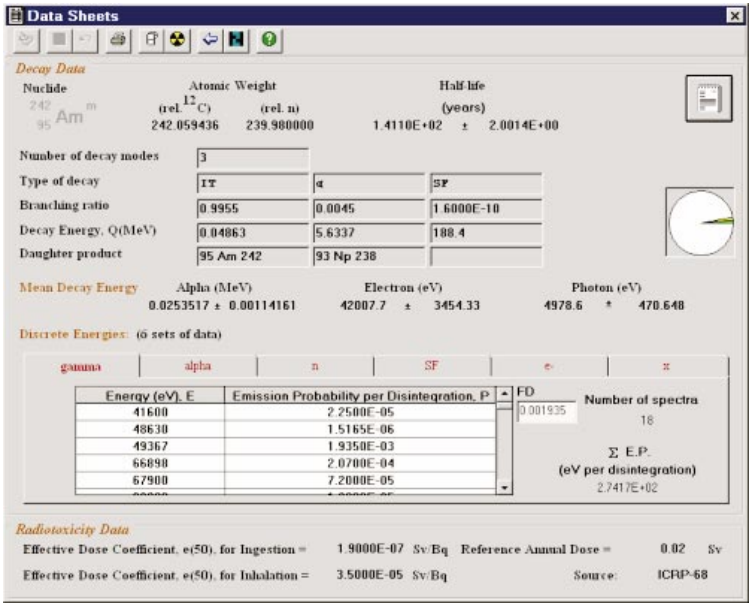


Fig. 5.2.1. *Data Sheet window showing decay data for the selected nuclide.*

Atomic Weight

The atomic weight or atomic weight ratio M of an atom is defined as the ratio of the mass of that atom relative to some reference mass. The reference mass is usually that of ^{12}C or the neutron. The atomic mass unit, the amu, is defined as 1/12 the mass of a ^{12}C atom and is described in more detail in Appendix 1. This quantity can be used to calculate the decay energy for a particular decay process. Consider the decay of U-238 i.e.

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + \alpha(^{4}_{2}He)$$

In a later section it is shown that the decay energy for alpha emission, Q_α, is given by

$$Q_\alpha = [M(^{238}U) - M(^{234}Th) - M(^{4}He)]c^2$$

where c is the speed of light. On the atomic weight scale, the quantity $M(^{238}U) - M(^{234}Th) - M(^{4}He) = 0.0048$ amu $= 0.0048 \times 931.49432$ MeV $= 4.47117$ MeV.

Half-life

The probability that an atom will decay during the time dt is given by kdt where k is the constant of proportionality known as the decay constant. In a system where there are N(0) atoms present initially, the number of atoms decaying in time dt is given by $-dN = kNdt$. In the limit of very small time intervals, this can be expressed as

$$dN/dt = -kN$$

Integration with respect to time gives the number of atoms present at any time t i.e.

$$N(t) = N(0)e^{-kt}$$

In practice, one uses the half-life τ to denote the time at which the number of atoms has dropped to half the initial value $1/2 = e^{-k\tau}$. Hence the half-life is related to the decay constant through the relation $\tau = \ln 2/k \approx 0.693/k$.

Number of Decay Modes

There are a number of ways in which a nuclide can decay. Usually the number of decay modes is one or two. There are nuclides, however, which have up to four decay modes (e.g. ^{181}Hg). As an example, the four decay modes of the nuclide ^{181}Hg are listed in *table 5.1.*

Table 5.1. *Decay modes, branching ratios, decay energies, and daughter products of ^{181}Hg.*

Decay Mode	ε/β^+	$\varepsilon/\beta^+, \alpha$	ε/β^+, p	α
Branching Ratio	0.8699	9×10^{-8}	1.4×10^{-4}	0.13
Decay Energy, Q(MeV)	7.07	12.985	6.3	6.289
Daughter Product	^{181}Au	^{177}Ir	^{180}Pt	^{177}Pt

Decay Modes

The main decay modes by which a radionuclide can decay are:

- Alpha (α) decay
- Beta-minus (ß-) decay
- Gamma emission
- Isomeric transitions (IT)
- Beta-plus (ß+) decay
- Electron capture (ε)
- Spontaneous fission (SF)
- Proton decay (p)
- Special beta-decay processes ($ß^-$ n, $ß^+$ α, $ß^+$ p)
- Heavy-ion radioactivity (^{14}C, ^{24}Ne)

A description of each of these modes is given in the Appendix 2.

Branching Ratios (BR)

In section 5.2.1 the radioactive decay by a single process or decay mode was considered. Many nuclides have, however, more than one decay mode. Consider a nuclide in which there are two decay modes. From the previous discussion, the probability that an atom will decay by process 1 in time dt is k_1dt. Similarly the probability that it will decay by process 2 in time dt is k_2dt. Hence the equation governing the radioactive decay can be written as

$$dN/dt = -(k_1+k_2)N$$

The total decay constant for the decay of the parent nuclide is $k=k_1+k_2$.

Hence, the branching ratios for modes 1 and 2 are defined as

$$BR_1 = k_1/k, \text{ and } BR_2 = k_2/k$$

In general, the *branching ratio (BR)* for a particular decay mode is defined as the ratio of the number of atoms decaying by that decay mode to the number of particle decaying in total i.e.

$$BR_i = k_i/(k_1+k_2+\ldots k_i+\ldots) = k_i/k$$

Alternatively, given the total decay constant, the "partial" decay constant is given by

$$k_i = BR_i . k$$

This is described in more detail in section 5.3.

Decay Energy, Q

The decay energy Q is the total energy released in the decay process. Consider the decay process

$$x \rightarrow y + z$$

where x, the parent nuclide decays to daughter y through the emission of a particle z. From conservation of energy

$$E_x+M_xc^2 = E_y+E_z+M_yc^2+M_zc^2$$

where E_x, E_y, E_z are the kinetic energies of x, y, and z respectively and M_xc^2, M_yc^2, M_zc^2 their rest-mass energies. Hence the change in the kinetic energies before and after the decay, i.e. the total decay energy Q

$$Q = (E_y + E_z) - E_x = [M_x - (M_y + M_z)]c^2$$

is then equal to the difference in the rest mass energies. As an example, consider the decay of uranium-238:

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + \alpha(^{4}_{2}He)$$

About 77% of the α particles emitted have a kinetic energy of 4.20 MeV and 23% have an energy of 4.15 MeV. The 4.20 MeV transition results in the ground state of Th-234. The 4.15 MeV transition gives rise to an excited state which then decays by the emission of a 0.05 MeV photon to the ground state. Thus the total decay energy is 4.20 MeV plus the recoil energy of the thorium nucleus. From conservation of momentum, the momentum p of the alpha particle and the thorium nucleus must be equal. Since the energy E is related to the momentum by $E = p^2/2M$, it follows that the energy of the recoiling thorium nucleus is $E_{th} = (4/234) \times E_\alpha = 0.07$ MeV. Hence the total decay energy Q is 4.27 MeV. This can also be obtained from mass differences using the relation:

$$Q_\alpha = E_{Th} + E_\alpha - E_U = [M(^{238}U) - M(^{234}Th) - M(^{4}He)]c^2$$

where M is the atomic weight and c is the speed of light.

Daughter Products

The daughter products are the result of the decay process. In the case of ^{181}Hg, there are four daughter products as shown in *table 5.1*. When a mode of decay is by spontaneous fission (SF), no daughter product is given. In some cases (e.g. ^{258}Lr) a mode of decay and branching ratio are given but no

daughter product. This implies simply that no information is available for this daughter (i.e. ^{258}No).

5.2.2. Mean Decay Energies per Disintegration

The mean energies per disintegration is given for the three general radiation types $E_{\text{“}\alpha\text{”}}$, $E_{\text{“}\beta\text{”}}$, and $E_{\text{“}\gamma\text{”}}$, and the sum of these quantities is the total average energy (neutrinos excluded) available per decay to the decay heat problem. $E_{\text{“}\beta\text{”}}$ is the average energy of all “electron related” radiation such as ß-, ß+, conversion electrons etc. $E_{\text{“}\alpha\text{”}}$ is the average energy of all particles such as alpha particles, heavy charged particles from spontaneous fission, protons, and delayed neutrons and also includes the recoil energy. $E_{\text{“}\gamma\text{”}}$ is the average energy of all “electromagnetic” radiations such as gamma and x rays, and annihilation radiation.

5.2.3. Discrete Energies–Spectral Information

When a nuclide decays by particle emission, it may decay to an excited state of the daughter nucleus. The particle emitted will have a lower energy than had the parent decayed to the daughter ground state. In addition, the excited daughter will decay normally by gamma emission. Hence the particles and photons emitted in the decay process will have discrete energies and associated emission probabilities per disintegration. Various radiation types can result i.e. γ, ß-, ε/ß+, α, n, SF (spontaneous fission fragments), p, e-, and x-rays. In this section of the Data Sheets the discrete energies and emission probabilities per disintegration are listed. In addition, the total number of discrete emissions are given together with $\Sigma_i E_i \cdot P_i$ i.e. the average energy for a particular emission type. In the edit mode (see section 5.2.6), the quan-

tity "FD" appears. This is a normalisation factor for the emission probabilities.

5.2.4. Radiotoxicity

The radiotoxicity of a nuclide is determined by its *effective dose coefficient* e(T) (ref. A), which accounts for radiation and tissue weighting factors, metabolic and biokinetic information. The quantity T is the integration time in years following intake. For *adult workers*, the integration time is 50 years, such that the radiotoxicity (in Sievert, Sv) resulting from intake of a particular nuclide is the product of the effective dose coefficient (units Sv/Bq) and the activity (in Bq) of that nuclide i.e.

$$\text{Radiotoxicity} = \text{Activity} \times e(50)$$

For members of the public, these dose coefficients should be reduced further to reflect intake at an earlier age (*ref. B*). Further details on the effective dose and the Sievert are given in Appendix 3.

References:

A International Commission for Radiological Protection, *Dose Coefficients for Intake of Radionuclides by Workers*, Annals of the ICRP publication **68**, Pergamon Press (1994).

B International Commission For Radiological Protection, *Age-dependent Dose Coefficients to Members of the Public from Intake of Radionuclides: Parts 1-3 Ingestion Dose Coefficients*, Annals of the ICRP publications **56** (1989), **67** (1993), **69** (1995), Pergamon Press.

5.2.5. Derived Quantities

With the basic nuclide data given in the Data Sheets (see *fig. 5.2.1*) various useful quantities can be derived. These are listed in the Derived Quantities window shown in *fig. 5.2.2*. In this section, a discussion of these various quantities is given together with the formula on which they are based.

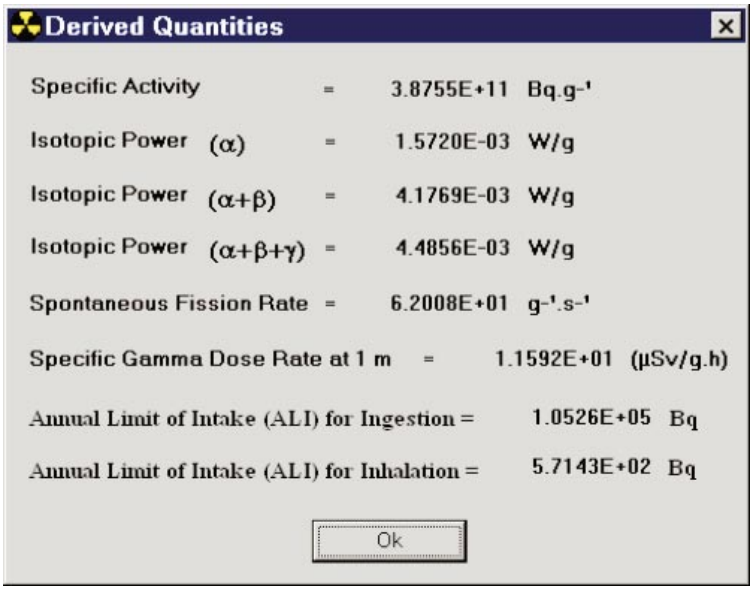


Fig. 5.2.2. *Derived Quantities window is accessed from the Data Sheets.*

Specific Activity

The number of decays per unit time interval, i.e. the activity A, is defined

$$A = -dN/dt = kN$$

It should be noted in this definition that it is assumed that N is decreasing due to decay. In general the rate equation for a species j contains a term for decay to the daughter and growth from the parent i.e.

$$dN_i/dt = -k_iN_i + k_{i-1}N_{i-1}$$

A situation could arise in which $\lambda_iN_i = \lambda_{i-1}N_{i-1}$ and thus N_i is constant i.e. $dN_i/dt=0$. Clearly the activity is not zero. In the definition of A above only decay is considered. In the general case where decay and growth occur, A is given by $A_i = -k_iN_i$. Hence A_i tells us how many disintegration per second are occurring even though N_i may be constant. The unit of activity is the Becquerel i.e. 1 Bq = 1 disintegration per second.

A technical problem arises in the evaluation of the activity in the case where the half-life is less than 1 s. The activity defined above gives the instantaneous disintegration rate. If the half-life is ≤ 1 s a significant amount of the material has decayed in the first second. The above definition of the activity will then overestimate the emitted radiation. The difficulty can easily be overcome by defining the activity per integral second i.e.

$$A_{1s} = \int_0^1 kNdt = N_0(1-e^{-k})$$

where $k=\ln 2/t_{1/2}(s)$. For the calculation of the specific activity A (activity per gram of material), the N_0 in the above relation is the number of atoms in 1 g, i.e. $N_0=(1\ g)/[AWR_n \cdot m_n(g)]$ such that the specific activity can be expressed as

$$A = N_0(1-e^{-k}) = (1-e^{-k})/[AWR_n \cdot m_n(g)]$$

or

$$A(Bq/g) = 5.970 \cdot 10^{23} \cdot (1\text{-}\exp(-\ln 2/t_{1/2}(s)))/AWR_n$$

Isotopic Power

The range of alpha and beta particles in solid material is small. As a result, radionuclides can generate substantial amounts of heat due to the kinetic energy of the emitted particles being transformed into heat. If all the emitted alpha and beta particles are retained in the material, the Isotopic Power, i.e. the heat generated per unit time per unit mass is given by

$$\text{Isotopic Power } (\alpha) = A \cdot [E_{\text{“}\alpha\text{”}}]$$
$$\text{Isotopic Power } (\alpha+\beta) = A \cdot [E_{\text{“}\alpha\text{”}}+E_{\text{“}\beta\text{”}}]$$

Where A is the specific activity, and $E_{\text{“}\alpha\text{”}}$ and $E_{\text{“}\beta\text{”}}$, the average energies per disintegration associated with heavy particles and electrons discussed in the section 5.2.2. The units of isotopic power are (W/g). If one is interested in bulk material, it is useful to consider in addition the deposition of the gamma energy in the material. Hence we have

$$\text{Isotopic Power } (\alpha+\beta+\gamma) = A \cdot [E_{\text{“}\alpha\text{”}}+E_{\text{“}\beta\text{”}}+E_{\text{“}\gamma\text{”}}]$$

The values of the isotopic power given in the data sheets are for the parent isotope only. In some cases, the parent decays to a short-lived daughter, which can also contribute strongly to the isotopic power. Some important examples are Sr90 (daughter Y90 half-life 2.6d), Ru106 (daughter Rh106 half-life 29.8s), Cs137 (daughter Ba137m half-life 2.55m), Ce144 (daughter Pr144 half-life 17.3m). In such cases, one has to evaluate the full decay chain.

Spontaneous Fissions (SF)

The rate of spontaneous fission (SF) is given by

$$\text{Spontaneous Fission Rate} = A.BR^{SF}$$

Where A is the specific activity, and BR^{SF} is the branching ratio for spontaneous fission. Since the number of neutrons emitted in spontaneous fission is between 2 and 3, the SF rate is closely related to the neutron emission rate.

Specific Gamma Dose Rate at 1m

In Appendix 3, it is shown that the gamma dose rate is given by

$$dH/dt = = 1.373\times10^{-5}\, G(keV/s)/(4\pi R(cm)^2) \qquad (\mu Sv/hr)$$

where G is the gamma emission rate (keV/s) and R is the distance from the source. This expression is valid for a point source. For R = 100 cm the expression reduces to

$$dH/dt|_{1m} = 1.093\times10^{-10}\, G(keV/s) \qquad (\mu Sv/hr)$$

For 1 g of nuclide, the specific gamma emission rate G is given by

$$G(keV/s\cdot g) = A(Bq/g)\cdot(\Sigma_i E_i(keV)\cdot P_i)$$

It follows that the specific gamma dose rate at 1m is

$$dH/dt|_{1m} = 1.093\times10^{-10}\, A(Bq/g)\cdot(\Sigma_i E_i(keV)\cdot P_i) \quad (\mu Sv/h\cdot g)$$

Annual Limits of Intake

A useful quantity in connection with radiation exposure is the Annual Limit of Intake or ALI value. The ALI value is the Annual Limit of Intake for a particular radionuclide and can be obtained by dividing the reference annual average dose (0.02 Sv for workers) by the dose coefficient i.e.

$$\mathrm{ALI(Bq)} = 0.02\ \mathrm{Sv}/e(50)$$

The ingestion and inhalation radiotoxicities are given by

$$\mathrm{RTIng} = A \cdot e_{ing}(50), \qquad \mathrm{RTInh} = A \cdot e_{inh}(50)$$

where A is the specific activity and e the effective dose coefficient.

5.2.6. Editing the Data Sheets

During installation, the original database used in *Nuclides 2000* is copied to the hard disk. This database should be regarded as a "personal" database in which data can be added, removed, changed etc. The original database is located on the CD-ROM and can be restored at any time.

Configure the Personal Database

The personal database on the hard disk, however, is installed in a read-only mode. Before the user can edit this basic data, the mode of operation must be changed. This is done from the Nuclide Navigation window (shown in *fig. 5.1.2*) by selection of the *Tools* button, and then *Configure the Personal Database*. The default read-only option can then be

deactivated. Thereafter the button to edit the data sheets is enabled.

Import from Original Database

After the user has been working with the personal database for some time, probably some existing data has been modified, some isotopes have been added and/or deleted. At any time, however, the original database can be restored through the *Tools* button and then *Import from Original Database*.

In the Open Personal Database dialog box, the user is requested to locate the personal database file "personal.mdb". On entering this selection, a further dialogue box requests the user to import a set of nuclides (i.e. a single nuclide, a group of nuclides or all nuclides) from the original database. Acceptance of this set of nuclides (by pressing OK) will result in the data for these nuclides in the personal database being overwritten by the original data.

> Before new isotopes can be added to the database or existing isotopes edited, the read-only option for the database must first be deactivated as explained above.

New Isotopes

New elements cannot be entered into the *Nuclides 2000* database. Elements up to atomic number 114 are already included although only default data have been used for elements 113 and 114. This can be changed when real data becomes available. The International Union for Pure and Applied Chemistry (IUPAC) has devised a systematic naming scheme for

new elements. Following their recommendations the elements have the names and symbols shown in *table 5.2*. Also shown are the abbreviations for elements 110-114 used in *Nuclides 2000*.

Table 5.2. *Naming of new elements.*

element	IUPAC name	symbol	Abbreviation used in *Nuclides 2000*
110	Un un nil ium	Uun	Un
111	Un un un ium	Uuu	Uu
112	Un un bi lum	Uub	Ub
113	Un un tri lum	Uut	Ut
114	Un un quad ium	Uuq	Uq

For any element, isotopes can be added from the nuclide explorer window using the isotope list box. First select the element. Then from the taskbar at the top of the window select *add new isotope*. Thereafter, the Data Sheets window opens in the edit mode. The minimum data required to add a new isotope is mass number and the atomic weight ratio relative to the neutron (for elements 110-114, where the atomic weight ratio is not yet known, the atomic weight relative to ^{12}C is approximately equal to the mass number. From this, the atomic weight relative to the neutron can be calculated using the relations given in Appendix 1, section 3). If no further data is added, the half-life is assumed to be zero and the isotope sta-

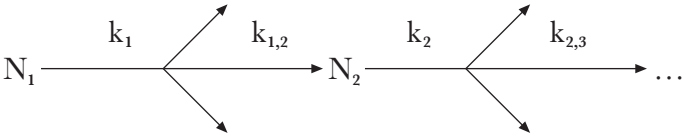
ble. If a half-life is entered, then additional data on the number of decay modes, type of decay, branching ratio, and daughter product are required.

Editing Existing Isotopic Data

The basic isotopic data given in the Data Sheets can be edited. In the Data Sheets window, the data for a particular isotope can be edited by selecting the *edit* button in the taskbar. Thereafter the data sheets window changes to the edit mode.

5.3. Decay Calculations

The process of radioactive decay is described by the Bateman equations (see for example Skrable, K., *et al.*, *Health Physics*, **27**, 1972, 155-157). The equations govern linear first order processes of the form:



The differential equation governing the above process can be written as:

$$dN_1/dt = -k_1N_1$$
$$dN_2/dt = k_{1,2}N_1 - k_2N_2$$
$$\cdots$$
$$dN_n/dt = k_{n-1,n}N_{i-1} - k_nN_n$$
$$dN_N/dt = k_{N-1,N}N_{N-1}$$

where N_n is the number of atoms of species n present at time t, k_n is the decay constant (total removal constant) for species n ($k=\ln(2)/\tau_{1/2}= 0.69315/\tau_{1/2}$), $k_{n,n+1}$ is the partial decay constant (partial removal constant) and is related to the branching ratio $BR_{n,n+1}$ through the relation $k_{n,n+1}=BR_{n,n+1} \cdot k_n$. The solution to this system of equations is

$$N_n(t) = \sum_{i=1}^{i=n} \left[\left(\prod_{j=1}^{j=n-1} k_{j,j+1} \right) \sum_{j=1}^{j=n} \frac{N_i(0) e^{-k_j t}}{\prod_{\substack{p=i \\ p \neq j}}^{p=n} (k_p - k_j)} \right]$$

for the particular case (of most interest) we are interested in the decay chain starting from a single parent nuclide. In this case the above relation reduced to:

$$N_n(t) = \prod_{j=1}^{j=n-1} k_{j,j+1} \sum_{j=1}^{j=n} \frac{N_i(0) e^{-k_j t}}{\prod_{\substack{p=i \\ p \neq j}}^{p=n} (k_p - k_j)} \qquad (5.3.1)$$

It is of interest to construct the first few terms i.e.

$$N_1 = N_1(0) e^{-k_1 t}$$

$$N_2 = k_{1,2} \left\{ \frac{N_1(0) e^{-k_1 t}}{k_2 - k_1} + \frac{N_1(0) e^{-k_2 t}}{k_1 - k_2} \right\}$$

$$N_3 = k_{1,2} k_{2,3} \left\{ \frac{N_1(0) e^{-k_1 t}}{(k_2 - k_1)(k_3 - k_1)} + \frac{N_1(0) e^{-k_2 t}}{(k_1 - k_2)(k_3 - k_2)} + \frac{N_1(0) e^{-k_3 t}}{(k_1 - k_3)(k_2 - k_3)} \right\}$$

etc.

These relations allow one to update the numbers of atoms from time t=0 to time t. It is also of interest to calculate the numbers at various times up to the time t (for example for plotting purposes). This can be done by specifying the total time t over which the calculation is to be made, and the number of time-steps L to reach t. The time interval for each calculation is then $\Delta t = t/L$. For L=1 (the default value used in the calculation), the numbers are evaluated at the time t. For L=2, the numbers are evaluated at t/2, and t. For L=3, the Ns are evaluated at t/3, 2t/3, t etc. From above, the relation to be used is then

$$N_n((l+1)\Delta t) = \sum_{i=1}^{i=n}\left[\left(\prod_{j=1}^{j=n-1} k_{j,j+1}\right)\sum_{j=1}^{j=n}\frac{N_i(l\Delta t)e^{-k_j\Delta t}}{\prod_{\substack{p=i\\p\neq j}}^{p=n}(k_p-k_j)}\right]$$

$$\text{for } l = 1, 2, 3, \ldots L \qquad (5.3.2)$$

To do a decay calculation within *Nuclides 2000*, the user must first select a parent nuclide using the *Nuclide Explorer* as described in section 5.1. In the taskbar shown in *fig. 5.1.2*, the user then selects the decay "tree" button. The resulting window is shown in *fig. 5.3.1*. In the top left of *fig. 5.3.1*, the input data can be entered. This consists of the initial quantity of the parent nuclide in grams, Becquerel or Curie and the time at which the calculation is to be made. The default values are 1 g and ten half-lives of the parent nuclide respectively. The distance (default value 100 cm) is optional and is only required for the calculation of the gamma dose rate dH/dt from a point source. The number of time steps is also optional (default value is 1) and is required only to obtain intermediate values for plotting purposes (see *fig. 5.3.4*). The results shown in *fig. 5.3.1* are for the decay of Am242m.

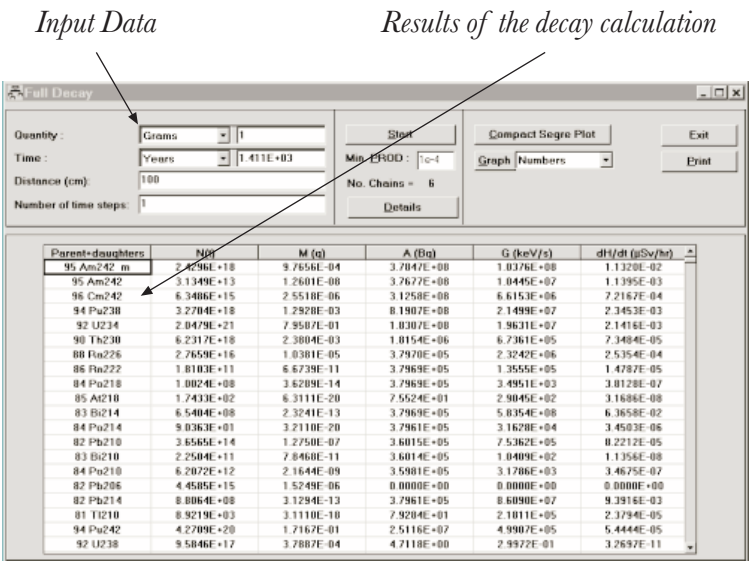


Fig. 5.3.1. *Decay calculation window.*

The results show the parent and all the daughters of Am242m in the first column. Internally, all the linear decay chains have been evaluated. More information on the decay chain evaluations can be seen by pressing the *Details* button. The *Details* window is shown in *fig. 5.3.2*. In this window all the individual decay chains can be seen together with the numbers obtained by using equation 5.3.1. The importance of a decay chain is determined by the product PROD of the branching ratios (section 5.2.1). If the branching ratios were all 1, there would only be one chain and PROD=1.0. If a particular branching ratio in a decay chain is small e.g. 1E-8, and all other branching ratios were 1, then the product would be 1E-8. This implies that this particular decay chain is relatively less important. One must be careful in neglecting such chains, however, since the concentration or

mass of the relevant nuclide may be small but may have a very high gamma emission rate. An example is the decay of U232. If only the main chain were considered (i.e. the chain with the highest PROD value) one would miss the daughter Tl208 which is a powerful gamma emitter. This is discussed in more detail in the Case Studies in section 7.2.

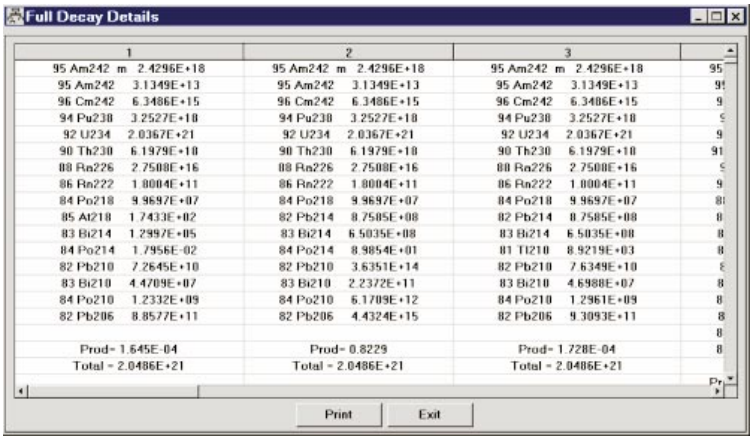


Fig. 5.3.2. *Details of the decay calculation.*

Ideally, one would like to evaluate all the decay chains for a particular parent nuclide. The problem is, however, that some heavy nuclides have a large number of decay chains– Lr255 has for example 544 separate decay chains! To apply equation 5.2.1 to all these chains would impose a considerable burden on the PC. Fortunately, in most cases of interest, this is not necessary. It is sufficient to restrict the number of chains to less than ten. The parameter used to restrict the number of chains to be evaluated is the product of the branching ratios PROD for the particular chain. The minimum value i.e. Min. PROD can be set in the top right of *fig.*

5.3.1. The default value is 1E-4. When the Start button in *fig. 5.3.1* is pressed, the branching ratios of all decay chains are evaluated and compared to this value. If the product of the branching ratios is less than Min PROD, the chain is rejected as being unimportant. If greater, the chain is stored for further evaluations. The number of chains stored–No. Chains–i.e. with the product of the branching ratios ≥ Min. PROD, is given at the top right of *fig. 5.3.1*. In the case shown, six chains have the product of the branching ratios greater or equal to 1E-4. If Min.PROD is set to 0, all chains are evaluated but as stated above, this may take some time. The details of these six chains are given in *fig. 5.3.2*. When these six chains are merged together, the results given in the first two columns of *fig. 5.3.1* are obtained. Once the numbers have been calculated, the masses, activities, gamma emission rates and the gamma dose rates are calculated as described in section 5.2.5. With this information the decay chain can be shown on a compacted Segrè plot by pressing the *Compact Segrè Plot* button. The resulting window is shown in *fig.5.3.3*.

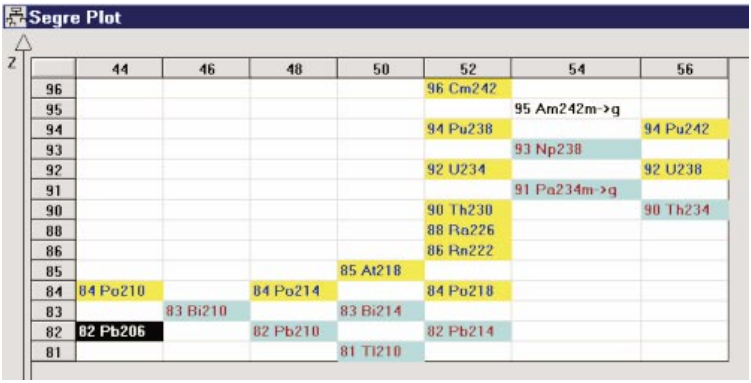
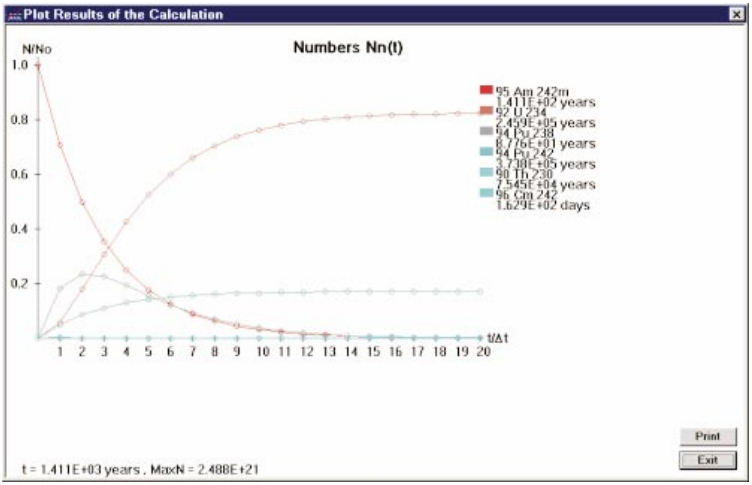


Fig. 5.3.3. *Compacted Segrè plot of the decay scheme.*

In contrast to the Segrè chart shown in *fig. 5.1.2*, this compacted plot is a Z vs. A-2Z diagram of the decay scheme. Because the x co-ordinate is A-2Z rather than A-Z (=N), decay by alpha emission results in a series of daughters aligned vertically. For complicated decay processes, this results in a more compact presentation of the decay process. The compacted Segrè plot can be printed directly in colour. For users who have access only to a black/white printer, the colours can be represented by various shades of grey. The colour scheme can be selected in the *Options* menu as discussed in section 5.1. The user could define, for example, a colour scheme with the name "B/Wprinter", and define the colours appropriately. Before printing the compacted Segrè plot, this colour scheme is chosen. Finally, a graph of the results can be obtained with the *Graph* button. A graph requires that the results have been obtained at intermediate values between times 0 and t. The number of steps can be set in input data section of *fig. 5.3.1.* The default value here is 1 to keep the number of calculations and therefore computing time to a minimum. The maximum value is 20. In the list box below the *Graph* button, the user can choose which quantity should be shown i.e. numbers, masses, activities etc.

Fig. 5.3.4 shows the graph of the results for Am242m decay. In the lower left corner, the time at which the decay chain is evaluated is given. In this case, the results have been calculated at 20 intervals. Only the six most important nuclides are shown. The number of atoms is normalised to the maximum number which in this case occurs at time t=0. On the top right, the various curves are associated with the parent and daughter nuclides. Also shown is the half-life of the respective nuclide. These results can also be printed.

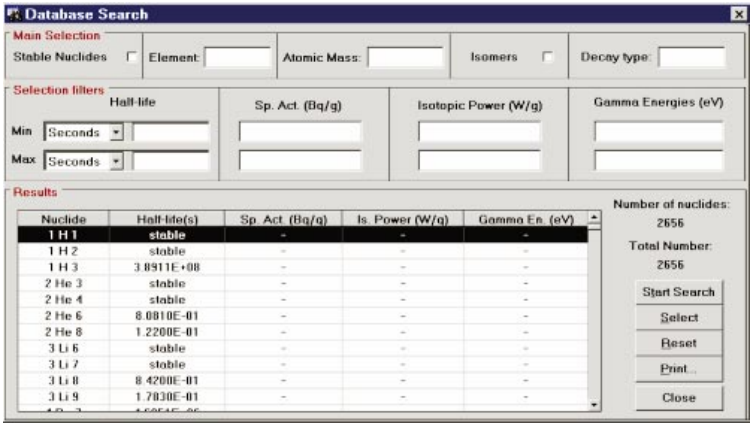


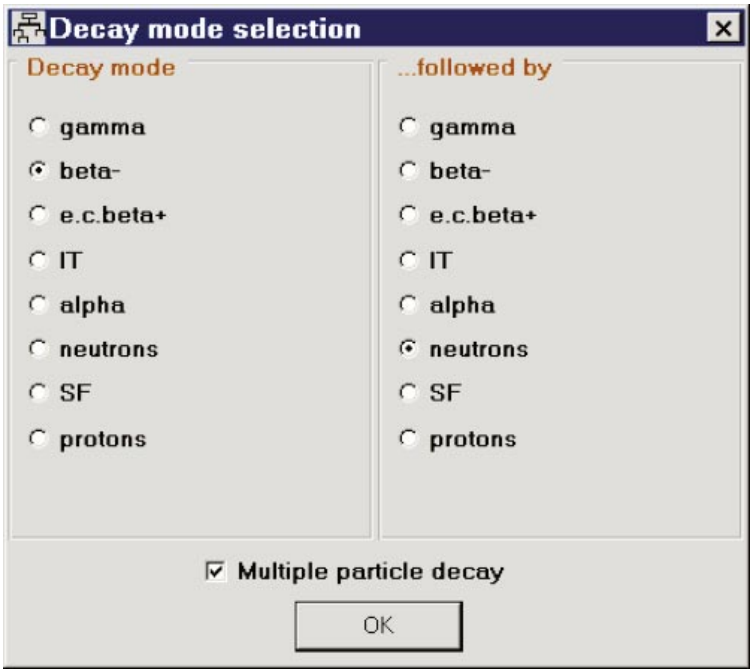
Searching the Database

-lides with particular characteristics. The nuclide search en gine can be accessed from the navigational interfaces shown in *figs. 5.1.1* and *5.1.2* by pressing the *Database Search* button in the taskbar.

in the database is obtained by pressing the *Start Search* but ton. The total number of gamma energies can be found by entering a zero in the Min. Gamma Energies box. The re sult is over 70,000 (this search can take a few minutes to complete). Search operations to find the stable nuclides, iso mers etc. are straightforward. In addition, comprehensive Boolean search tasks can be performed. Searches can also be performed on the *Decay type* (e.g. alpha, ß-, etc.). To per

form this task the user should double click in the *Decay type* box. A new window opens as shown in *fig. 5.4.2*. In the win dow shown, a main decay mode ß- has been checked. In ad--dition, *multiple particle decay* and *n* has been checked. This im plies that the decay mode which has been selected is ß-,n i.e. beta emission followed by neutron emission (delayed neu tron emission). On pressing *OK*, followed by *Start Search* in *fig. 5.4.1*, the database will be searched for this type of decay.

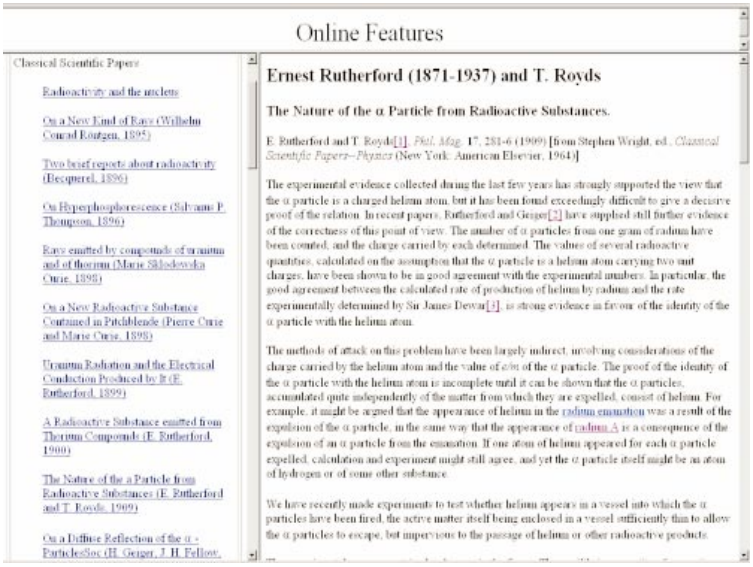



Decay mode selection
Decay mode
gamma
beta-
e.c.beta+
IT
alpha
neutrons
SF
protons
...followed by
gamma
beta-
e.c.beta+
IT
alpha
neutrons
SF
protons
Multiple particle decay
OK

6. Online Resources

In the Online Resources the browser window opens with the *Nuclides 2000* homepage. From an investigation of internet related websites, documents have been classified under the following general headings:

Glossary of Nuclear Science, Classical Scientific Papers, Historical, People, New Elements, Origin of Nuclides, Introduction to Radiation and Radioactivity, Applications of Radionuclides, Archaeology, Radon, Nuclear Data, Others, Organisation.



In the selection shown, a classical scientific paper by Rutherford and Royds on *The Nature of the* α *Particle from Radioactive Substances* is shown.

7. Examples

7.1. Case Study: The Radioactive Decay of the Nuclide ^{60}Co

The nuclide ^{60}Co is unstable and decays by the process of β^- emission (emission of a negatively charged electron from the nucleus), to a stable isotope of the element nickel i.e. ^{60}Ni. This decay process can be written:

$$^{60}_{27}\mathrm{Co}(\tau_{1/2}=5.27\,\mathrm{y}) \rightarrow {}^{60}_{28}\mathrm{Ni}(\mathrm{stable}) + {}_{-1}\beta^- \tag{7.1}$$

The halflife of ^{60}Co is 5.27 years. The differential equations governing the decay process (7.1) are written:

$$dN_{Co}/dt = -kN_{Co} \qquad dN_{Ni}/dt = +kN_{Co}$$

where N_{Co} denotes the concentration or total number (depending on the context) of Co atoms. The constant of proportionality (see section 5.2.1) $k=\ln(2)/\tau_{1/2}=0.69315/\tau_{1/2}$. The solution to the above equations is given by:

$$N_{Co}(t)=N_{Co}(0)\exp(-kt) \qquad N_{Ni}(t)=N_{Co}(0)(1-\exp(-kt)) \tag{7.2}$$

Number of Atoms at Time t

For the above example, we consider a starting mass M=1 g of the nuclide ^{60}Co. The number N of cobalt atoms in 1 g is given by

$$N = M(g)/(AWR_n * m_n(g)) \qquad (7.3)$$
$$= 1/(59.4189 * 1.67493\times10^{-24}) = 1.0048\times10^{22}$$

The decay constant k is given by

$$k = \ln(2)/\tau_{1/2} = \ln(2)/(5.2711\ y * 3.1536\times10^{7}\ s/y)$$
$$= 4.1698\times10^{-9}\ s^{-1}$$

The number of atoms normalised to the starting number, the actual number, and the masses at the times 1s, 1d, 1w, 1m, 1y, 10y, 100y are obtained using relations (7.2) and (7.3) and given in *table 7.1.1.*

Table 7.1.1. *Number of (Co) atoms N, masses M, activities A, gamma emission rates G, and dose rate at 1m $dH/dt|_{1m}$ resulting from the decay of 1 g of ^{60}Co at various times.*

Time	N/N0	N	M (g)	A (Bq)	G (keV/s)	$dH/dt|_{1m}$ (μSv/h)
1s	1.0000E+00	1.0048E+22	1.0000E+00	4.1898E+13	1.05E+17	1.15E+07
1d	9.9964E-01	1.0044E+22	9.9964E-01	4.1883E+13	1.05E+17	1.15E+07
1w	9.9748E-01	1.0023E+22	9.9748E-01	4.1793E+13	1.05E+17	1.14E+07
1m	9.8925E-01	9.9400E+21	9.8925E-01	4.1448E+13	1.04E+17	1.13E+07
1y	8.7678E-01	8.8099E+21	8.7678E-01	3.6736E+13	9.20E+16	1.01E+07
10y	2.6848E-01	2.6976E+21	2.6848E-01	1.1249E+13	2.82E+16	3.08E+06
100y	1.9456E-06	1.9549E+16	1.9456E-06	8.1516E+07	2.04E+11	2.23E+01

The Activity

The number of decays per unit time interval, i.e. the activity A (5th column of *table 7.1.1*), is described in section 5.2.5.

The Gamma Emission Rate

When 1g ^{60}Co decays, the emission of the ß- particle is accompanied by gamma rays. There are six gamma lines and emission probabilities associated with each disintegration as shown in *table 7.1.2*. An emission probability P=1 for a given energy line implies that one photon of this energy is emitted per disintegration. The total gamma emission per disintegration is therefore

$$G(keV/s)=A(Bq)\cdot(\Sigma_i E_i(keV).P_i)=A(Bq)\cdot(2.50\times10^3(keV))$$

where the value for $\Sigma_i (E_i \cdot P_i)$ from *table 7.1.2* has been substituted. The total gamma emission rates from ^{60}Co at various times are shown in the 6th column of *table 7.1.1.*

Table 7.1.2. *The energies and intensities of the six gamma lines associated with the decay of ^{60}Co.*

Energy E (keV)	Emission Probability P (per disintegration)	Product E*P (keV/disintegration)
346.93	7.60E-05	2.64E-02
826.28	7.60E-05	6.28E-02
1173.2	9.99E-01	1.17E+03
1332.5	9.99E-01	1.33E+03
2158.8	1.10E-05	2.37E-02
2505	2.00E-08	5.01E-05
	Σ E.P=	2.50E+03

The Dose Equivalent Rate

From Appendix 3, the dose equivalent rate from a point source at distance R is given by

$$dH/dt|_R = 1.373\times10^{-5}\, G(keV/s)/(4\pi R(cm)^2) \qquad (\mu Sv/hr)$$

The dose equivalent rate from the 1g ^{60}Co source at a distance of 1m is shown in the last column of *table 7.1.1.*

7.2. Case Study: The Radioactive Decay of the Nuclide ^{232}U

The decay of the nuclide ^{232}U is considerably more complex than that of ^{60}Co in that the ^{232}U gives rise to a series of daughter products before decaying to stable ^{208}Pb.

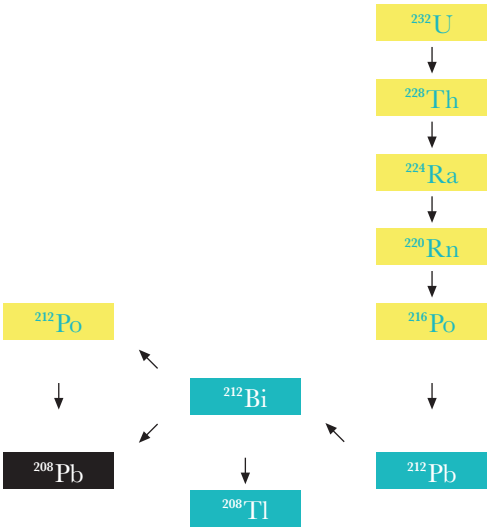


Fig. 7.1. *The ^{232}U decay chain.*

The Decay Process

The decay process of the nuclide ^{232}U is shown in *fig. 7.1.* In the program, this can be obtained by selecting the nuclide ^{232}U and then the *full decay chain* button. After pressing *chain evaluation*, the full decay chain can be seen in the *Segrè Plot* window. It can be seen that ^{212}Bi has three distinct decay modes and results in three separate decay chains.

Number of nuclei at time t

In the present example, an initial mass of 1g ^{232}U is chosen. The program calculates the number of atoms of ^{232}U at time t=0. The conversion from the mass to number is through the atomic weight ratio and is described in Appendix 1. The number of atoms initally is given by

$$N(t=0) = M(t=0) / [AWR_n \cdot m_n] = 2.595331 \times 10^{21}$$

The calculations are performed at times t=10 y, 100 y, 1000 y. From the number of atoms at time t, masses, activities, gamma emission rates and dose equivalent rates are obtained as described previously. The results are shown in *tables 7.2.1-7.2.3*. The gamma emission rate for each nuclide n is

$$G_n(\text{keV/s}) = A_n(\text{Bq}) \cdot (\Sigma_j E_j(\text{keV}) \cdot P_j)_n$$

where $(\Sigma_j E_j(\text{keV}) \cdot P_j)_n$ is the gamma emission per disintegration for nuclide n and A_n is the activity. The gamma emission rates are shown in *table 7.2.4.*

Table 7.2.1. *Number of atoms N, masses M, activities A, gamma emission rates G, and dose equivalent rate at 1m $dH/dt|_{1m}$, resulting from the decay of 1g ^{232}U at t=10y.*

Nuclide	N(t)	M (g)	A (Bq)	G (keV/s)	$dH/dt|_{1m}$ (μSv/hr)
U232	2.3501E+21	9.0553E-01	7.3954E+11	1.64E+11	1.79E+01
Th228	6.4269E+19	2.4336E-02	7.3791E+11	1.47E+12	1.60E+02
Ra224	3.3297E+17	1.2386E-04	7.3791E+11	7.11E+12	7.77E+02
Rn220	5.9190E+13	2.1624E-08	7.3791E+11	5.11E+11	5.58E+01
Po216	1.5436E+11	5.5367E-11	7.3791E+11	1.07E+10	1.17E+00
Pb212	4.0777E+16	1.4354E-05	7.3790E+11	8.46E+13	9.25E+03
Bi212	3.8676E+15	1.3615E-06	7.3790E+11	7.81E+13	8.53E+03
Po212	2.0455E+05	7.2005E-17	4.7261E+11	0.00E+00	0.00E+00
Pb208	1.8054E+20	6.2350E-02	0.0000E+00	0.00E+00	0.00E+00
Tl208	7.0129E+13	2.4220E-08	2.6519E+11	8.96E+14	9.78E+04
Total	2.5953E+21	9.9235E-01	5.9047E+12	1.07E+15	1.16E+05

Table 7.2.2. *Number of atoms N, masses M, activities A, gamma emission rates G, and dose equivalent rate at 1m $dH/dt|_{1m}$, resulting from the decay of 1g ^{232}U at t=100y.*

Nuclide	N(t)	M (g)	A (Bq)	G (keV/s)	$dH/dt|_{1m}$ (μSv/hr)
U232	9.6207E+20	3.7069E-01	3.0275E+11	6.70E+10	7.32E+00
Th228	2.7111E+19	1.0266E-02	3.1128E+11	6.18E+11	6.75E+01
Ra224	1.4048E+17	5.2257E-05	3.1132E+11	3.00E+12	3.28E+02
Rn220	2.4972E+13	9.1233E-09	3.1132E+11	2.16E+11	2.36E+01
Po216	6.5126E+10	2.3359E-11	3.1132E+11	4.51E+09	4.93E-01
Pb212	1.7204E+16	6.0563E-06	3.1133E+11	3.57E+13	3.90E+03
Bi212	1.6318E+15	5.7441E-07	3.1133E+11	3.29E+13	3.60E+03
Po212	8.6301E+04	3.0379E-17	1.9940E+11	0.00E+00	0.00E+00
Pb208	1.6060E+21	5.5463E-01	0.0000E+00	0.00E+00	0.00E+00
Tl208	2.9588E+13	1.0219E-08	1.1189E+11	3.78E+14	4.12E+04
Total	2.5953E+21	9.3565E-01	2.4819E+12	4.51E+14	4.91E+04

Table 7.2.3. *Number of atoms N, masses M, activities A, gamma emission rates G, and dose equivalent rate at 1m $dH/dt|_{1m}$, resulting from the decay of 1g ^{232}U at t=1000y.*

Nuclide	N(t)	M (g)	A (Bq)	G (keV/s)	$dH/dt|_{1m}$ (μSv/hr)
U232	1.2716E+17	4.8996E-05	4.0015E+07	8.86E+06	9.68E-04
Th228	3.5833E+15	1.3568E-06	4.1143E+07	8.17E+07	8.93E-03
Ra224	1.8568E+13	6.9070E-09	4.1149E+07	3.97E+08	4.33E-02
Rn220	3.3007E+09	1.2059E-12	4.1149E+07	2.85E+07	3.11E-03
Po216	8.6079E+06	3.0875E-15	4.1149E+07	5.96E+05	6.51E-05
Pb212	2.2740E+12	8.0048E-10	4.1149E+07	4.72E+09	5.16E-01
Bi212	2.1568E+11	7.5922E-11	4.1149E+07	4.35E+09	4.76E-01
Po212	1.1407E+01	4.0153E-21	2.6355E+07	0.00E+00	0.00E+00
Pb208	2.5952E+21	8.9626E-01	0.0000E+00	0.00E+00	0.00E+00
Tl208	3.9111E+09	1.3507E-12	1.4790E+07	5.00E+10	5.45E+00
Total	2.5953E+21	8.9631E-01	3.2807E+08	5.96E+10	6.50E+00

Table 7.2.4. *The total γ energies per decay.*

Nuclide	$\Sigma_j E_j \cdot P_j$ (eV/disintegration)
U232	2.2131E+02
Th228	1.9854E+03
Ra224	9.6390E+03
Rn220	6.9267E+02
Po216	1.4488E+01
Pb212	1.1470E+05
Bi212	1.0583E+05
Po212	0.0000E+00
Pb208	0.0000E+00
Tl208	3.3779E+06

Appendices

Appendix 1: The Atomic Weight Ratio AWR

1. The atomic weight ratio AWR of a nuclide is defined as the ratio of the mass of that nuclide (nucleus) to that of a reference mass. In the database used in *Nuclides 2000*, the reference mass used is that of a free neutron i.e. $m_n = 1.6749286 \times 10^{-24}$ g. The AWR values given in the database are given by

$$AWR_n = \text{mass of nucleus} / m_n$$

where the subscript in AWR_n indicates the reference mass. Consider the nucleus of the nuclide ^{232}U. From the database $AWR_n = 230.044$. It follows that the mass of a ^{232}U nucleus is

$$m_{232U} = AWR_n \cdot m_n = 3.853072 \times 10^{-22} \text{ g}$$

2. Another scale that is commonly used is on the basis of ^{12}C. The reference mass used is then 1/12 of the mass of the ^{12}C nucleus. This scale is defined such that 12 g of ^{12}C contain 6.0221367×10^{23} atoms (Avogadro's number). Hence the mass of a ^{12}C nucleus is

$$m_{12C} = 12 \text{ g} / (6.0221367 \times 10^{23} \text{ atoms}) = 1.992648 \times 10^{-23} \text{ g}$$

The atomic weight ratio on this basis, i.e. AWR_{12C}, is defined by

$$AWR_{12C} = \text{mass of nucleus} / (m_{12C} / 12)$$

As an example consider the nuclide ^{208}Pb. In the *Handbook of Physics and Chemistry*, the atomic weight ratio is on the ^{12}C scale. On this scale $AWR_{12C}=207.976627$. It follows that the mass of a ^{208}Pb nucleus is

$$m_{208Pb}=AWR_{12C}\cdot(m_{12C}/12)$$
$$=207.976627\cdot(1.992648\times10^{-23}\ g/12)$$

or

$$m_{208Pb}=3.453535\times10^{-22}\ g$$

From the above definitions, the atomic weight ratio on the neutron scale i.e. AWR_n of this nucleus is given by

$$AWR_n=\text{mass of nucleus}/m_n=206.1899$$

and this is the value used in the database.

3. From the relations given above, it follows that

$$AWR_n\cdot m_n=AWR_{12C}\cdot(m_{12C}/12)$$

or

$$AWR_n=AWR_{12C}\cdot(m_{12C}/12)/m_n$$

It follows that

$$AWR_n=AWR_{12C}\cdot(0.9914094)$$

As an example, consider ^{228}Th. For the value $AWR_{12C}=228.028715$, it follows that $AWR_n=226.0698$.

Calculations in *Nuclides 2000* usually involve entering a mass of a parent nuclide. The first internal calculation is to convert this mass to a number of atoms before the solutions to the equations is evaluated. The relation used for this conversion is, from the above considerations,

$$\text{number of atoms} = (\text{mass of the nuclide in grams} / \text{neutron mass in grams}) \cdot (1/\text{AWR}_n)$$

where the first term in brackets is atomic weight ratio of all the atoms to that of a neutron. Further division by the AWR_n for a particular nuclide results in the total number of atoms of that nuclide.

Appendix 2: Types of Radioactivity

Radioactive nuclides decay spontaneously in the following modes:

- Alpha (α) decay
- Beta-minus (β^-) decay
- Gamma emission
- Isomeric transitions (IT)
- Beta-plus (β^+) decay
- Electron capture (ε)
- Spontaneous fission (SF)
- Proton decay (p)
- Special beta-decay processes ($\beta^- n$, $\beta^+\alpha$, $\beta^+ p$)
- Heavy-ion radioactivity (^{14}C, ^{24}Ne)

Alpha (α) decay:

The alpha particle emitted in this type of radioactivity is a doubly charged ion of helium, i.e ^{4}He(2+) or simply ^{4}He. All alpha particles emitted by a nuclide either have the same energy or have at most a few different energy values. Energies of the alpha particles lie in the range of 2-8 MeV. An example is the decay of uranium-238:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + \alpha\,(^{4}_{2}\mathrm{He})$$

In the interaction with matter, the alpha particles give up their energy and become neutral helium atoms. Their range in solids and liquids is very short–of the order of μm. In air the range is typically a few cm. Because of this short range, they do not normally constitute a hazard to humans. They are absorbed in the outer layers of the skin before they cause injury. If the alpha particles are taken internally, for example by ingestion or inhalation, they are very toxic because of the large amount of energy released in a short distance within living tissue. Indeed, this property can be used for killing cancer cells in the process of alpha-immunotherapy.

Beta-minus (ß-) decay:

Beta radioactivity occurs when a nucleus emits a negative electron and occurs when the nuclide has too many neutrons. Beta emission differs from alpha emission in that beta particles have a continuous spectrum of energies between zero and some maximum value, the endpoint energy, characteristic of that nuclide. This endpoint energy corresponds to the mass difference between the parent nucleus and the daughter as required by conservation of energy. The aver-

age energy of the beta particle is approximately 1/3 of the maximum energy. The distribution of energies is explained by postulating that a second particle, the neutrino ν, is emitted along with the electron and that the sum of the energies carried by the electron and the neutrino equals the maximum observed beta energy. More precisely, the "neutrino" emitted in beta-minus decay is the anti-neutrino (with neutrino being emitted in beta-plus decay). The neutrino has zero charge and almost zero mass. The maximum energies of the beta particles range from 10 keV to 4 MeV. Although beta-minus particles have a greater range than alpha particles, thin layers of water, glass, metal, etc. can stop them. An example is the decay of Th-234:

$$^{234}_{92}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + \beta^{-} + \nu$$

Gamma emission:

Gamma emission is not a primary decay process but usually accompanies alpha and beta decay. Typically this type of radiation arises when the daughter product resulting from alpha or beta decay is formed in an excited state. This excited state returns to the ground state through the emission of a gamma photon. Alternatively, the excited nucleus may return to the ground state by ejecting an orbital electron. This is known as internal conversion and results in an energetic electron and X-rays due to electrons cascading to lower energy levels. The ratio of internal conversion to gamma emission is known as the internal conversion coefficient. Instead of having a well-defined range like alpha and beta particles, gamma rays loose characteristically a certain fraction of their energy per unit distance through matter. Gamma rays are highly penetrating and can result in considerable organ-

ic damage. Gamma emitting sources require heavy shielding and remote handling.

Isomeric transitions (IT):

In contrast to normal gamma emission that occurs by dipole radiation, isomeric transitions must occur by higher order multipole transitions that occur on a longer time-scale. If the lifetime for gamma emission exceeds about one nanosecond, the excited nucleus is defined to be in a metastable or isomeric state. The decay process from this excited state is known as an isomeric transition (IT). An example is the decay of the isomer or metastable state of protactinium i.e.

$$^{234m}_{91}\mathrm{Pa} \rightarrow {}^{234}_{91}\mathrm{Pa} + \gamma$$

with a half-life $\tau_{1/2} = 1.17$ min. and a branching ratio of 0.0013. The letter m after the mass number denotes the metastable state.

Beta-plus (ß+) decay:

When a nucleus has too many protons, a positron (a positively charged electron) can be created and emitted, along with a neutrino. Within the nucleus a proton is converted into a neutron, a positron, and a neutrino. Similarly to the ß-, the positron ß+ is continuously distributed in energy up to a characteristic maximum energy. The positron, after being emitted from the nucleus, undergoes strong electrostatic attraction with the atomic electrons. The positron and negative electrons annihilate each other and result in two photons (gamma rays) each with energy of 0.511 MeV moving in opposite directions. An example is the decay of C-11:

$$^{11}_{6}C \rightarrow {}^{11}_{7}B + \beta^{+} + \nu$$

Electron Capture (ε):

Some nuclei can capture an electron from the inner K or L shells of the atomic orbits. As a result, a proton in the nucleus transforms to a neutron. The process is similar to β^{+} decay in that the charge of the nucleus increases by 1. The resulting nucleus is unstable and decays by the ejection of an unobservable neutrino (ν) and the emission of an x-ray when the electron vacancy in the K or L shell is filled by outer orbit electrons. An example is the electron capture process in beryllium i.e.

$$^{7}_{4}Be + e^{-} \rightarrow {}^{7}_{4}Li + \nu$$

Spontaneous Fission (SF):

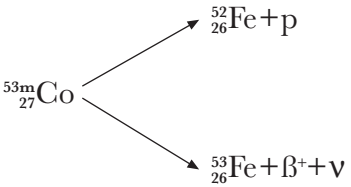
Actinides (U, Pu, Am, Np ,Cm, etc.) can undergo radioactive decay by spontaneous fission. In this process the nucleus splits into two fragment nuclei, with mass and charge roughly half that of the parent, and several neutrons. For fermium, one such reaction is as follows:

$$^{256}_{100}Fe \rightarrow {}^{140}_{54}Xe + {}^{112}_{46}Pd + 4n$$

where only one of many fission product combinations is shown. The kinetic energy release in this process, due mainly to large electrostatic repulsion of the fragments, is approximately 190 MeV.

Proton decay:

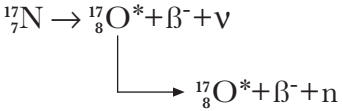
This decay process, discovered in 1970, is exhibited by the metastable state of cobalt-53, i.e.



with branching ratios of 1.5% (p mode) and 98.5% (β^{+} mode).

Special beta-decay processes:

One such process is beta-delayed neutron emission ($\beta^{-}n$), which is exemplified by the following reaction:



(Note: the asterisk denotes the short-lived intermediate excited states of oxygen-17).

Among the positron emitters in the light-element region, a number beta decay partly to excited states that are unstable with respect to emission of an alpha particle ($\beta^{+}2\alpha$). Thus, these species exhibit alpha radiation with the half-life of the beta emission. Both the positron decay from boron-8 and negatron decay from lithium-8 ($\beta^{-}2\alpha$) are beta-delayed alpha emission, because ground as well as excited states of

beryllium-8 are unstable with respect to breakup into two alpha particles. Another example, sodium-20 (^{20}Na) giving successively neon-20 (^{20}Ne; the asterisk again indicating the short-lived intermediate state) and finally oxygen-16 is listed below:

$$^{20}_{11}\mathrm{Na} \rightarrow {}^{20}_{10}\mathrm{Ne}^{*} + \beta^{+} + \nu$$
$$\rightarrow {}^{17}_{8}\mathrm{O}^{*} + \alpha$$

In a few cases, positron decay leads to an excited nuclear state not able to bind a proton. In these cases, proton radiation appears with the half-life of the beta transition. The combination of high positron-decay energy and low proton-binding energy in the daughter ground state is required. In the example given below, tellurium-111 (^{111}Te) yields antimony-111 (^{111}Sb) and then tin-110 (^{110}Sn) successively

$$^{111}_{52}\mathrm{Te} \rightarrow {}^{111}_{51}\mathrm{Sb}^{*} + \beta^{+} + \nu$$
$$\rightarrow {}^{110}_{50}\mathrm{Sn}^{*} + \mathrm{p}$$

Heavy-ion radioactivity:

In 1980 A. Sandulescu, D.N. Poenaru, and W. Greiner described calculations indicating the possibility of a new type of decay of heavy nuclei intermediate between alpha decay and spontaneous fission. The first observation of heavy-ion radioactivity was that of a 30-MeV, carbon-14 emission from radium-223 by H.J. Rose and G.A. Jones in 1984. The ratio of carbon-14 decay to alpha decay is about 5×10^{-10}. Observations also have been made of carbon-14 from radium-222, radium-224, and radium-226, as well as neon-24

from thorium-230, protactinium-231, and uranium-232. Such heavy-ion radioactivity, like alpha decay and spontaneous fission, involves quantum-mechanical tunnelling through the potential-energy barrier. Shell effects play a major role in this phenomenon and in all cases observed to date the heavy partner of carbon-14 or neon-24 is close to doubly magic lead-208.

Adapted with permission from "Types of radioactivity" in "Atoms: Their Structure, Properties and Component Particles", *Britannica CD 98 Multimedia Edition*, © 1994-1998 Encyclopaedia Britannica, Inc.

Appendix 3: The Gamma Dose Rate

The evaluation of the gamma dose rate described in this section follows closely that given in J. R. Lamarsh, *Introduction to Nuclear Engineering*, 2nd edition, Addison-Wesley 1983.

Absorbed Dose D

The absorbed dose to the mass δm, is defined as the imparted energy per unit mass i.e.

$$D = \delta E / \delta m$$

The conventional unit of absorbed dose is the rad (radiation absorbed dose) and is equal to 0.01 J/kg. The S.I. unit of absorbed dose is the gray, Gy. This is defined as an absorbed dose of 1 J/kg. Hence,

$$1\ \text{Gy} = 1\ \text{J/kg} = 100\ \text{rad}$$

The absorbed dose rate is the rate at which an absorbed dose is received. The units are Gy/s, mGy/hr, etc.

Quality Factor

The biological effect of radiation is not directly proportional to the energy deposited by radiation in an organism. It depends in addition on the way in which the energy is deposited along the path of the radiation. Thus the biological effect of the radiation increases with the linear energy transfer (LET). Thus for the same absorbed dose, the biological effect from high LET radiation such as α particles or neutrons is much greater than that from low LET radiation such as ß or γ rays.

The term quality is used to describe the fact that energy may be deposited in different ways along its path. The quality factor is introduced to account for this difference in the biological effects of different types of radiation.

Dose Equivalent

The dose equivalent H is defined as the product of the absorbed dose and the quality factor i.e.

$$\text{H(dose equivalent)} = \text{D(absorbed dose)} \cdot \text{Q(quality factor)}$$

It should be clear that equal dose equivalents from different sources of radiation delivered to a point in the body should produce approximately the same biological effect. It should be noted, however, that a given dose equivalent will in general produce different effects in different parts of the body. A dose to the hand may be considerably less serious than the

same dose to blood forming organs. The S.I. unit of dose is the Sievert, Sv. This is the dose equivalent arising from an absorbed dose of 1 Gy.

The Sievert, Sv, describes the biological effect of radiation deposited in an organism. The biological effect of radiation is not just directly proportional to the energy absorbed in the organism but also by a factor describing the *quality* of the radiation. An energy deposition of 6 J per kg of gamma radiation (quality=1) i.e. 6 Sv is lethal. This same energy deposited in the form of heat (quality=0) will only increase the body temperature by 1 mK and is therefore completely harmless. The difference between the two types of radiation is due to the fact that biological damage arises from ionisation. The annual effective dose equivalent from natural sources is typically 3 mSv.

Hence for γ rays, where Q=1, an absorbed dose of 1 Gy gives a dose equivalent of 1 Sv. The same absorbed dose for α particles, where Q=20, gives a dose equivalent of 20 Sv. The dose equivalent rate is the rate at which a dose equivalent is received i.e.

$$dH/dT = dD/dt \cdot Q$$

The dose equivalent rate is expressed in Sv/s or μSv/hr.

Calculation of Dose and Dose Equivalent Rates

The dose rate or energy deposition rate per unit mass in tissue is given by

$$dD/dt = I \cdot E\,(\mu_a/\rho)^{tis}$$

The quantities I and E are usually expressed in photons $cm^{-2}\ s^{-1}$ and MeV respectively, and (μ_a/ρ) in $cm^2\ g^{-1}$. The units of dD/dt are then $MeV/g \cdot s$. To convert to S.I. units (the S.I. unit of absorbed dose is the gray, Gy, where 1 Gy=1 J/kg)

$$dD/dt = 1.60217733 \times 10^{-10}\ I \cdot E \cdot (\mu_a/\rho)^{tis} \qquad (Gy/s)$$

In the energy range 0.1 MeV<E<10 MeV, $(\mu_a/\rho)^{tis} \cong (\mu_a/\rho)^{air} = 2.38 \times 10^{-2}\ cm^2 \cdot g^{-1}$. Hence

$$dD/dt = 3.813 \times 10^{-12}\ I \cdot E \qquad (Gy/s)$$

or

$$dD/dt = 1.373 \times 10^{-8}\ I \cdot E \qquad (Gy/hr)$$

for gamma radiation, the quality factor Q=1 so that the dose rate and dose equivalent rate are equal, hence

$$dD/dt == 1.373 \times 10^{-8}\ I \cdot E \qquad (Sv/hr)$$

or

$$dD/dt == 1.373 \times 10^{-2}\ I \cdot E \qquad (\mu Sv/hr)$$

The quantity $(I \cdot E)$ has units $MeV \cdot cm^{-2} \cdot s^{-1}$. In *Nuclides 2000*, the total gamma energy emission rate from a nuclide is denoted by G (see section 5.2.4.) and has units of $keV \cdot s^{-1}$. If one assumes that the nuclide is a point source, then the energy per unit area per unit time at a distance R is given by $G/(4\pi R^2)$ assuming no attenuation due to absorption. The quantity I.E in the above relations can then be replaced by

$$I \cdot E = 10^{-3} G/(4\pi R^2)$$

The constant 10^{-3} is due to the fact that G is determined in keV rather than MeV. Hence

$$dD/dt = = 1.373 \times 10^{-5}\, G/(4\pi R^2) \qquad (\mu Sv/hr)$$

where G is expressed in keV/s and R in cm.

Appendix 4: The Nuclides 2000 Database

Errors in the JEF 2.2 Datafile

The data used in *Nuclides 2000* is based on the JEF 2.2 datafile in which the data is stored sequentially as an ASCII text file. In this form, the data is not suitable for efficient retrieval. For this reason, the JEF 2.2 datafile has been "converted" into a relational database for use in *Nuclides 2000*. In this form, efficient search tools allow fast data access.

In the course of this work, some errors were found in the JEF 2.2 datafile and these were corrected in the database. Previously known errors (for a list see http://www.nea.fr/html/dbdata/nds_eval_feedback.htm) have been removed where possible. In this section, the incorrect entries in the original JEF 2.2 datafile are given together with the corrections contained in the database. For those familiar with the JEF 2.2 datafile, the number RTYPE which uniquely characterises the decay modes in the datafile is shown in the tables below.

Pure decay modes:

mode	$ß^-$	$ε/ß^+$	IT	α	n	SF	p	^{14}C
RTYPE	1	2	3	4	5	6	7	8

Mixed decay modes (examples):

mode	$ß^-α$	$ß^-n$	$ε/ß^+α$	$ε/ß^+p$	ITα
RTYPE	1.4	1.5	2.4	2.7	3.5

In the following, a list of the original and corrected data is given:

1. Co^{53m}: The two decay modes are 2.0 and 7.0 instead of 2.0 and 2.7.

	Original…		Modified…	
Type of Decay	$ε/ß^+(2.0)$	$ε/ß^+p$ (2.7)	$ε/ß^+(2.0)$	p (7.0)
Branching Ratio	0.985	0.015	0.985	0.015
Decay Energy, Q	11.494	3.9644	11.494	3.9644
Daughter	26Fe53	25Mn52	26Fe53	25Fe52

2. N^{17}: The two decay modes are 1.0 and 1.5 instead of 1.0.

	Original…		Modified…	
Type of Decay	$ß^-$(1.0)		$ß^-$(1.0)	$ß^-n$(1.5)
Branching Ratio	1		0.049	0.951
Decay Energy, Q(MeV)	8.68		8.68	
Daughter	8O17		8O17	8O16

3. Na^{20}: The two decay modes are 2.0 and 2.4 instead of 2.0.

	Original…		Modified…	
Type of Decay	$ε/ß^+$(2.0)		$ε/ß^+$(2.0)	$ε/ß^+α$(2.4)
Branching Ratio	1		0.795	0.205
Decay Energy, Q(MeV)	13.887		13.887	
Daughter	10Ne20		10Ne20	8O16

4. Ra^{223}: The two decay modes are 4.0 and 8.0 instead of 4.0.

	Original…		Modified…	
Type of Decay	α(4.0)		α(4.0)	^{14}C(8.0)
Branching Ratio	1		1	6.1E-10
Decay Energy, Q(MeV)	5.9791		5.9791	
Daughter	86Rn219		86Rn219	

5. Ra^{222}: The two decay modes are 4.0 and 8.0 instead of 4.0.

	Original…		Modified…	
Type of Decay	α(4.0)		α(4.0)	^{14}C(8.0)
Branching Ratio	1		1	3.7E-10
Decay Energy, Q(MeV)	6.676		6.676	
Daughter	86Rn219		86Rn219	

6. Ra^{224}: The two decay modes are 4.0 and 8.0 instead of 4.0.

	Original…		Modified…	
Type of Decay	α(4.0)		α(4.0)	^{14}C(8.0)
Branching Ratio	1		1	4.3E-11
Decay Energy, Q(MeV)	5.7889		5.7889	
Daughter	86Rn220		86Rn220	

7. F^{18}: The emission probability for X radiation is 2.0. This has been set to 1.0 in the database.

8. Pr^{144}: The emission probabilities are all zero. The energies and emission probabilities have been replaced by (from *Table of Radioactive Isotopes*, E. Browne and R. B. Firestone, J. Wiley & Sons 1986)

Modified data for Pr^{144}

γ(keV)	Emission Probability per decay
696.543	1.34E-2
1489.21	2.72E-3
2185.75	7.0E-3

9. U^{235m}: mean energy associated with gamma decay set to 0.

10. Ground states for a variety of nuclides missing. The following data (from the *Table of Isotopes*) have been added:

Nuclide	AWR (rel.^{12}C)	AWR (rel.n)	Half-life	Decay Mode	BR	Daughter
66Dy147	146.930219	145.668	1.3m	ε/ß$^+$	1	Tb147
67Ho16	159.928885	158.555	25.6m	ε/ß$^+$	1	Dy160

Additional Nuclides

In addition to corrections to the JEF 2.2 datafile, the *Nuclides 2000* database contains over forty additional nuclides from the elements Lr, Rf, Db, Sg, Bh, Hs, Mt, and elements 110, 111, 112. The data used for these nuclides, and listed in the following table, has been taken from:

http://hpngp01.kaeri.re.kr/CoN/index.html

Nuclide	AWR (rel. ^{12}C)	AWR (rel. n)	Half-life	Decay Mode	Q (MeV)	BR	Daughter
103Lr252	252.09533	249.929679	1s	alpha (4.0)	9.15	0.9	Md248
				ε/ß$^+$(2.0)		0.09	No252
				SF (6)		0.01	

Nuclide	AWR (rel. ^{12}C)	AWR (rel. n)	Half-life	Decay Mode	Q (MeV)	BR	Daughter
103Lr253	253.095258	250.921017	1.3s	alpha (4.0)	8.99	0.9	Md249
				ε/ß+(2.0)	4.3	0.01	No253
				SF (6)		0.09	
103Lr254	254.096587	251.913744	13s	alpha (4.0)	8.75	0.78	Md250
				ε/ß+(2.0)	5.2	0.22	No254
				SF (6)		0.001	
103Lr261	261.106941	258.863875	39m	SF (6)		0.001	
104Rf253	253.100679	250.9263923	1.8s	alpha (4.0)	9.5	0.5	No249
104Rf254	254.100166	251.9172931	0.5ms	SF (6)		0.997	
				alpha (4.0)	9.3	0.003	No250
104Rf255			1.5s	SF (6)		0.52	
	255.101492	252.9100171		alpha (4.0)	9.3	0.48	No251
104Rf256	256.1011796	253.9011168	6.7ms	SF (6)		0.98	
				alpha (4.0)	8.952	0.022	No252
104Rf257	257.103072	254.8944023	4.7s	alpha (4.0)	9.25	0.796	No253
				ε/ß+(2.0)	3.4	0.18	Lr257
				SF (6)		0.024	
104Rf258	258.103568	255.8863035	12ms	SF (6)		0.87	
				alpha (4.0)	9.25	0.13	No254
104Rf259	259.105628	256.8797552	3.1s	alpha (4.0)	9.11	0.93	No255
				SF (6)		0.07	
				ε/ß+(2.0)	2.45	0.003	Lr259
104Rf260	260.106434	257.8719637	20.1ms	SF (6)		0.98	
				alpha (4.0)	9	0.02	No256
104Rf261	261.108752	258.8656712	65s	alpha (4.0)	8.81	0.8	No257
				ε/ß+(2.0)	1.8	0.1	Lr261
				SF (6)		0.1	
104Rf262	262.109918	259.8582365	1.2s	SF (6)		1	

Nuclide	AWR (rel. ^{12}C)	AWR (rel. n)	Half-life	Decay Mode	Q (MeV)	BR	Daughter
104 Rf 263	263.11254	260.8522454	10m	alpha (4.0)	8.3	0.3	No 259
				SF (6)		0.7	
105 Db 255	255.107398	252.9158724	1.6s	alpha (4.0)	9.6	0.8	Lr 251
				SF (6)		0.2	
105 Db 256	256.10811	253.9079877	2.6s	alpha (4.0)	9.5	0.7	Lr 252
				SF (6)		0.2	
				ε / ß$^+$ (2.0)		0.1	Rf 256
105 Db 257	257.107858	254.8991472	1.3s	alpha (4.0)	9.31	0.82	Lr 253
				SF (6)		0.17	
				ε / ß$^+$ (2.0)	4.3	0.01	Rf 257
105 Db 258	258.109438	255.8921231	20s	alpha (4.0)	9.55	0.67	Lr 254
				SF (6)		0.01	
				ε / ß$^+$ (2.0)	5.5	0.33	Rf 258
105 Db 260	260.111427	257.8769138	1.52s	alpha (4.0)	9.37	0.9	Lr 256
				SF (6)		0.05	
				ε / ß$^+$ (2.0)	4.6	?	Rf 260
105 Db 261	261.112106	258.8689963	1.8s	alpha (4.0)	9.27	0.5	Lr 257
				SF (6)		0.5	
105 Db 262	262.114153	259.8624352	34s	alpha (4.0)	9.21	0.64	Lr 258
				SF (6)		0.33	
				ε / ß$^+$ (2.0)	4	0.03	Rf 262
105 Db 263	263.115078	260.8547616	27s	alpha (4.0)	9.03	0.43	Lr 259
				SF (6)		0.57	
106 Sg 258	258.113151	255.8958042	2.9ms	alpha (4.0)	9.7	0?	Rf 254
				SF (6)		1	
106 Sg 259	259.114652	256.8887017	0.9s	alpha (4.0)	9.87	0.8	Rf 255
				SF (6)		0.2	
106 Sg 260	260.1144354	257.8798963	3.6ms	alpha (4.0)	9.92	0.5	Rf 256
				SF (6)		0.5	

Nuclide	AWR (rel. ^{12}C)	AWR (rel. n)	Half-life	Decay Mode	Q (MeV)	BR	Daughter
106 Sg 261	261.116199	258.8730542	0.23s	alpha (4.0)	9.81	0.9	Rf 257
				SF (6)		0.1	
106 Sg 263	263.118313	260.8579688	0.8s	alpha (4.0)	9.69	0.3	Rf 259
				SF (6)		0.7	
106 Sg 265	265.121066	262.843517	16s	alpha (4.0)	9.05	0.5	Rf 261
				SF (6)		0.5	
106 Sg 266	266.121928	263.835781	20s	alpha (4.0)	9.1	0.5	Rf 262
				SF (6)		0.5	
107 Bh 261	261.1218	258.8786071	11.8ms	alpha (4.0)	10.56	0.9	Db 257
				SF (6)		0.1	
107 Bh 262	262.123009	259.8712151	102ms	alpha (4.0)	10.42	0.8	Db 258
				SF (6)		0.2	
107 Bh 262 m	262.123009	259.8712151	8ms	alpha (4.0)	10.735	0.7	Db 258
				SF (6)		0.3	
107 Bh 264	264.12473	261.8557401	0.44s	alpha (4.0)	9.97	1	Db 260
108 Hs 263	263.12871	260.8682765	1s	alpha (4.0)	?	1	Sg 259
108 Hs 264	264.1284083	261.8593868	0.08ms	alpha (4.0)	10.8	0.985	Sg 260
				SF (6)		0.015	
108 Hs 265	265.130001	262.8523752	1.8ms	alpha (4.0)	10.82	0.91	Sg 261
				SF (6)		0.09	
108 Hs 267	267.131774	264.8369518	33ms	alpha (4.0)	?		
108 Hs 267 m	267.131774	264.8369518	50ms	alpha (4.0)	10.11	1	Sg 263
108 Hs 269	269.134114	266.8220905	13s	alpha (4.0)	9.73	1	Sg 265
109 Mt 266	266.13794	263.8516554	3. ms	alpha (4.0)	11.269	0.945	Bh 262
				SF (6)		0.055	
109 Mt 268	268.138816	265.8353427	0.07s	alpha (4.0)	10.7	0.945	Bh 264
110 Un 269*	≅ 269	266.6891286	0.17ms	alpha (4.0)		1	Hs 265
110 Un 271*	≅ 271	268.6719474	1.1ms	alpha (4.0)		1	Hs 267
110 Un 273*	≅ 273	270.6547662	0.18ms	alpha (4.0)		1	Hs 269

Nuclide	AWR (rel. ^{12}C)	AWR (rel. n)	Half-life	Decay Mode	Q (MeV)	BR	Daughter
111Uu272*	≅272	269.6633357	1.5ms	alpha (4.0)		1	Mt268
112Ub277*	≅277	274.6204038	0.24ms	alpha (4.0)		1	Un273
113Ut276**	≅276	273.6289944	1ms	alpha (4.0)		1	Uu272
114Uq281**	≅281	278.5860414	1ms	alpha (4.0)		1	Ub277

* Data from http://ie.lbl.gov/education/isotopes.htm, $AWR_{12C} \cong A$ (i.e. Z+N), $AWR_n = AWR_{12C} \cdot (0.9914094)$.

** Default data. Can be changed when experimental data becomes available.

Appendix 5: Physical Constants* and Conversion Factors

Physical Constants

Quantity	Symbol	Value
Electron mass	m_e	$9.109\,3897(54)\times10^{-31}$ kg $5.485\,79903(13)\times10^{-4}$ amu 0.510 999 06(15) MeV/c^2
Electron charge	E	1.60217733×10^{-4} C
Proton mass	m_p	$1.6726231(10)\times10^{-27}$ kg 1.007276 470(12) amu 938.27231(28) MeV/c^2
Neutron mass	m_n	$1.6749286(10)\times10^{-27}$ kg 1.008664 904(14) amu 939.56563(28) MeV/c^2
Alpha particle mass	m_α	4.0026 amu
Atomic mass unit, (1 amu=m(^{12}C)/12=1g/N_A)	amu	$1.6605402(10)\times10^{-27}$ kg 931.494 32(28) MeV/c^2
Speed of light	c	$2.99\,792\,458\times10^{8}$ m s^{-1}
Avogadro Number	N_A	$6.022\,1367(36)\times10^{23}$ mol^{-1}
Boltzmann constant	k	$1.380\,658(12)\times10^{-23}$ J K^{-1}

* *Handbook of Chemistry and Physics*, ed. D.R. Lide, 73rd ed., 1992-93.

Conversion Factors

1 year	3.1536E7 s
1 month**	2.62800E6 s
1 week	6.048E5 s
1 day	8.640E4 s
1 Curie	3.7E10 Bq

** 1 month = 1 year / 12 = 2.6280E6 s.

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Abstract
Radionuclides have many applications in agriculture, medicine, industry and research. For basic information on such radioactive materials, the *Chart of the Nuclides* has proved to be an indispensable tool for obtaining data and qualitative information on decay schemes and reaction paths. These *Charts* are, however, of limited use when one requires quantitative information on the decaying nuclide and its daughters.

This was the motivation for the development of the NUCLIDES 2000 software package. The radioactive decay data used in NUCLIDES 2000 is based on the Joint Evaluated File (JEF) version 2.2. The present version of the program contains decay data on more than 2600 radionuclides.

In the *Nuclide Explorer*, a powerful navigational interface allows fast access to the nuclides through a periodic table and Segrè chart. Alternatively, a search facility is available to find nuclides with particular properties. The basic data in the *Data Sheets* can be edited and appended, and the changes are stored in a "personal" database. Derived data consists of activities, gamma dose rate, isotopic powers, annual limits of intake (ALI), etc. Through the decay engine, one can investigate the *full decay* scheme of any radionuclide to obtain the activities, radiotoxicities, dose rates, etc., accounting for all the daughters, starting from an initial mass or activity of the parent nuclide.

In addition to the *Nuclide Explorer*, a series of articles covering various aspects of radionuclides ranging from radiocarbon dating to supernovae is included. A comprehensive selection of links to Internet related sites is provided where, for example, important historical scientific documents can be viewed in full text or further information can be obtained.

Developed by experts working on a daily basis with radionuclides, NUCLIDES 2000 is the first dedicated CD-ROM capable of providing comprehensive decay information. It has been designed to be extremely user-friendly and is thus likely to appeal to both non-experts and experts alike. The application is available on CD for Windows 95, 98 and NT operating systems.

The product is useful for anyone involved with radionuclides, their properties and applications, and is particularly suitable for anyone needing to calculate activities and dose rates such as health physicists, medical physicists and environmental agencies. It is also suitable for students at schools and universities and should prove to be an invaluable tool for professional scientists for everyday calculations.

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